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INDUSTRIAL EQUIPMENT SURVIVAL/RECOVERY FEASIBILITY PROGRAM DURING EVENT DICE THROW

The Boeing Company
P.O. Box 3707
Seattle, Washington 98124

31 December 1976

Final Report

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Inexpensive techniques for protecting industrial equipment from nuclear attack environments hold great promise for permitting early repair of industrial machinery and its restoration to production following an attack. Without protection typical industrial machines suffer "moderate" damage at about 5 psi and "severe" damage at about 10 psi. Equipment items representative of fragile machinery, normal machinery and rugged machinery were tested at 40, 80, 200, and 600 psi in the DICE THROW field test event executed

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20. ABSTRACT (Continued)

October 6, 1976. The test specimens were placed in trenches excavated at the four appropriate ranges from the DICE THROW explosive charge center. The specimens then were surrounded by a crushable material (aluminum chips) and covered at depths from one foot to five feet with earth material removed in excavating the trenches. The results of these experiments indicate that with the use of crushable fill and with burial depth sufficient to permit earth arching, machines can be protected against overpressures up to 600 psi. However, when depths of covering were too shallow for an earth arch to develop, severe damage occurred.

Table 1a. Conversion factors for U.S. customary to metric (SI) units of measurement.

To Convert From	To	Multiply By
angstrom	meters (m)	1.000 000 X E -10
atmosphere (normal)	kilo pascal (kPa)	1 013 25 X E +2
bar	kilo pascal (kPa)	1 000 000 X E +2
barn	meter^2 (m^2)	1 000 000 X E -28
British thermal unit (thermochemical)	joule (J)	1 054 350 X E +3
calorie (thermochemical)	joule (J)	4.184 000
cal (thermochemical)/cm^2	mega joule/m^2 (MJ/m^2)	4.184 000 X E -2
curie	*giga becquerel (GBq)	3 700 000 X E +1
degree (angle)	radian (rad)	1 745 329 X E -2
degree Fahrenheit	degree kelvin (K)	$t_K = (t°f + 459\ 67)/1\ 8$
electron volt	joule (J)	1 602 19 X E -19
erg	joule (J)	1 000 000 X E -7
erg/second	watt (W)	1.000 000 X E -7
foot	meter (m)	3 048 000 X E -1
foot-pound-force	joule (J)	1 355 818
gallon (U.S liquid)	meter^3 (m^3)	3 785 412 X E -3
inch	meter (m)	2 540 000 X E -2
jerk	joule (J)	1 000 000 X E +9
joule/kilogram (J/kg) (radiation dose absorbed)	Gray (Gy)	1.000 000
kilotons	terajoules	4 183
kip (1000 lbf)	newton (N)	4 448 222 X E +3
kip/inch^2 (ksi)	kilo pascal (kPa)	6 894 757 X E +3
ktap	newton-second/m^2 (N-s/m^2)	1 000 000 X E +2
micron	meter (m)	1 000 000 X E -6
mil	meter (m)	2 540 000 X E -5
mile (international)	meter (m)	1 609 344 X E +3
ounce	kilogram (kg)	2 834 952 X E -2
pound-force (lbs avoirdupois)	newton (N)	4.448 222
pound-force inch	newton-meter (N·m)	1 129 848 X E -1
pound-force/inch	newton/meter (N/m)	1 751 268 X E +2
pound-force/foot^2	kilo pascal (kPa)	4 788 026 X E -2
pound-force/inch^2 (psi)	kilo pascal (kPa)	6 894 757
pound-mass (lbm avoirdupois)	kilogram (kg)	4 535 924 X E -1
pound-mass-foot^2 (moment of inertia)	kilogram-meter^2 (kg·m^2)	4 214 011 X E -2
pound-mass/foot^3	kilogram/meter^3 (kg/m^3)	1 601 846 X E +1
rad (radiation dose absorbed)	**Gray (Gy)	1.000 000 X E -2
roentgen	coulomb/kilogram (C/kg)	2 579 760 X E -4
shake	second (s)	1 000 000 X E -8
slug	kilogram (kg)	1 459 390 X E +1
torr (mm Hg, 0° C)	kilo pascal (kPa)	1.333 22 X E -1

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (Gy) is the SI unit of absorbed radiation.

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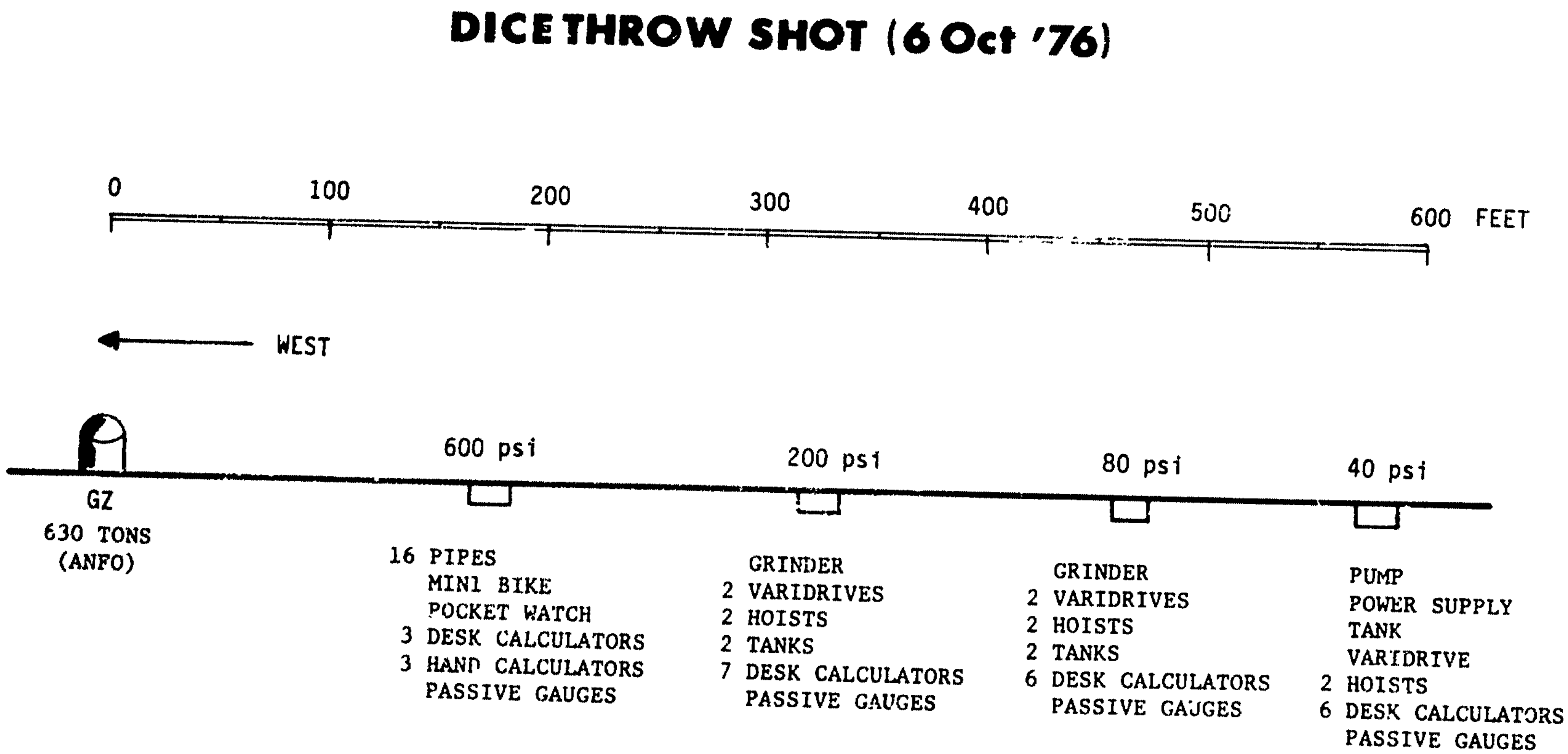


FIGURE 1a: TRENCH LOCATIONS AND ITEMS EMPLACED

INTRODUCTION

The purpose of this program was to determine whether simple and inexpensive techniques could be employed to protect industrial equipment against a nuclear attack. The goal was not to prevent damage entirely, but to limit damage sufficiently to allow speedy repair.

A typical industrial building is destroyed at about the 10 psi level. Usually it is assumed that if an industrial building is destroyed the machines inside the building will also be destroyed by the collapsing building. To achieve machine hardnesses considerably in excess of 10 psi, they must be protected from building debris, blast overpressure, dynamic pressure (winds), ground shock and possibly crater debris.

BACKGROUND

Boeing carried out an extensive survey of hardening techniques which could be employed utilizing concrete and steel, timber, soil, water and various crushable materials. Analyses indicated that inexpensive hardening could be achieved if earth arching could be shown to be effective under dynamic (blast) loading conditions.

Earth arching under static conditions has been utilized for centuries, e.g. in mine shafts and tunnels. The only requirement is to prevent the unsupported soil in the top of the shaft from collapsing ("chimneying") into the shaft. If this happens, the collapsing will often continue right up to ground level. To prevent such collapse some sort of structure is usually employed to reinforce the cavity. In a mine wood cribbing is often used; while in a tunnel a concrete or masonry tube is constructed. It is important to note, however, that such structures generally would not support the weight of soil directly above the shaft without the aid of soil arching into the soil beside the shaft.

The basic hardening technique studied here involves two separate aspects:

1. Provision of rattle space by packing the machine to be protected in a crushable material, and

2. Formation of an earth arch to protect the crushable material from the full force of the blast and ground shock.

It is important to note that if the earth arch failed, the crushable material, which has little inherent strength, would offer inadequate protection to prevent the buried machine from being extensively damaged or destroyed.

The following rationale and procedures were used to estimate rattle space dimensions and soil depth.

The crushable material must be strong enough to prevent contact between the soil arch and the machine, but crushable enough to prevent large forces from reaching the machine. Standard techniques used for packaging delicate instruments should carry over directly. (In fact all crushable materials tested were found to be suitable.) Good data are available on soil motion to be expected under given conditions, so the required rattle space can be found (see specific example below).

Depth of soil required for arching cannot now be calculated accurately since the angle of failure of soil is not known for dynamic blast loading with a flexible cavity (rattle space) under the arch. The static failure slip angle* (about 30^0 for most soils) was used for the 5 ton and DICE THROW tests and seems to be conservative. This angle gives the minimum depth of soil required for arching to occur.

Consider the following specific example: Suppose a small item, such as a hand calculator, is to be protected at the 600 psi range from a 1 kt burst (about the nuclear equivalent of DICE THROW for blast/shock effects). Maximum ground motion is about 6 in. To be conservative, the radius of a spherical rattle space will be taken as twice this value. The geometry to determine required soil depth is given in Figure 1b. Here a slip angle of 30^0 is assumed. A minimum soil depth of 12" is seen to be required above the rattle space. An additional 12" of soil is added to provide load distribution tamping action.

If a larger machine is to be protected then the soil thickness is determined by arching over its width (i.e., its smallest horizontal dimension.) The soil thickness found above (24") must be increased by about the machine width. For example in the case of the minibike emplaced at 600 psi at DICE THROW, the handle bar width was about 24", so the burial depth was 48".

In an actual hardening exercise the machines would probably not be buried in trenches (as was done in the experiments reported here), but would be buried in place in the factory in bags of crushable material and then covered with soil. Because of the close spacing of the machines in most shops this would result in a horizontal or near horizontal soil surface several feet above the machines.

A series of experiments were carried out by Boeing in preparation for the DICE THROW event. The first experiments were simple static overpressure model tests designed to determine whether crushable material (aluminum machining chips) would prevent chimneying and to get a feel for the depth of soil needed to form an earth arch. For example a shoe box enveloped in aluminum chips and covered with about one foot of soil was only slightly dished in under the static pressure (30 psi) imposed by driving a pickup truck onto the arch. This was followed by a full scale static and environmental test in which a large grinder was packed in crushable material,

*The slip angle as used here is the angle, measured from the vertical at which failure or slippage occurs when a soil column fails under a vertical static load.

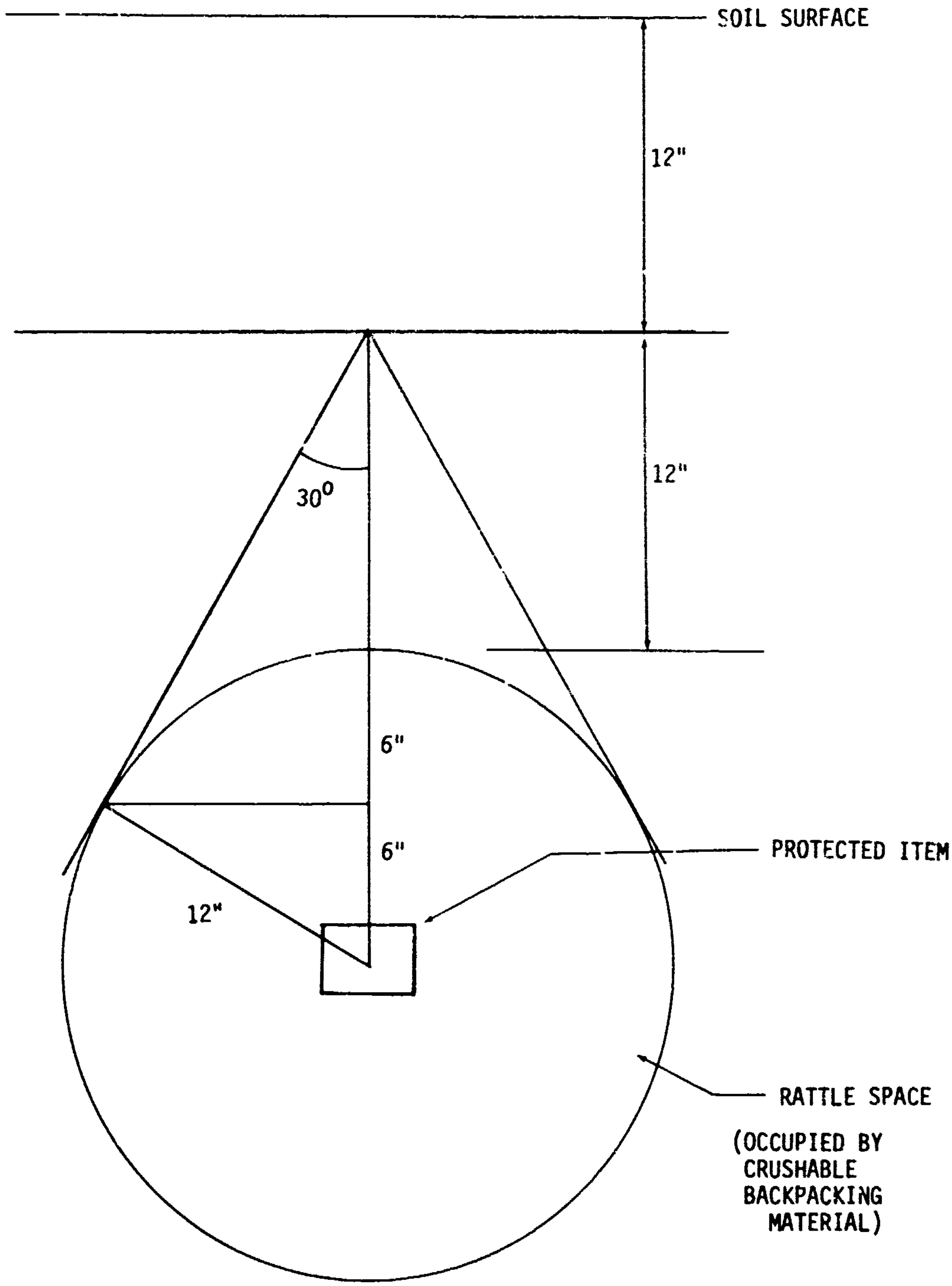


FIGURE 1b: GEOMETRY FOR DETERMINATION OF EARTH ARCH DEPTH

covered with soil and subjected to static overpressure by driving a front end loader onto the arch. The grinder remained buried for several weeks, during which interval more than three inches of rain fell, subjecting it to a realistic corrosion environment. The machine was recovered essentially undamaged.

Boeing next fielded a set of experiments in a DNA sponsored 5 ton TNT shot at Holloman AFB on August 25, 1976. The purpose was to test various inexpensive hardening techniques under dynamic conditions. The results of this test figured heavily in the test plan for the subject DICE THROW program. Therefore, the 5 ton test will be discussed here in some detail.

Four general classes of equipment were tested to represent various types of industrial equipment:

1. Seven electrical/mechanical desk calculators (one each at 20, 80 and 200 psi and two each at 40 and 300 psi). These were representative of soft industrial equipment such as power supplies.

2. Two varidrives (40 and 80 psi) and a vacuum pump (200 psi) to represent medium hard industrial equipment such as pumps and multi-base machines connected with mechanical power trains (e.g. five-axis mills).

3. Three electric chain hoists (80, 200 and 300 psi) to represent massive and inherently hard industrial machines such as grinders or lathes.

4. Five one gallon open top cans (one each at 20 and 80 psi and three at 200 psi) to represent industrial process and quench tanks which are inherently very soft.

Many different hardening techniques were tested on these eighteen items, based on techniques which could actually be used in hardening an industrial facility. Some machines would be preplaced on crushable bases which would still be rigid enough to prevent tolerance changes in day-to-day operations. This technique was simulated by placing some of the test equipment on styrene foam bases. Other machines would be light enough that they could be lifted and completely surrounded by loose crushable material. In the tests aluminum chips, styrene "worms" commonly used for shock protection in packaging fragile items for shipment and polyurethane blocks were used for this simulation.

The most straightforward way to protect the very soft process and quench tanks is to completely submerge them in water, cover them with a platform in contact with the water and then cover the platform with soil. Any shock wave passing through the water would traverse the tank material without damaging it. This technique was simulated by submerging open top one gallon cans in water filled garbage cans and burying the closed garbage can in soil.

Passive gauges of various types were emplaced in soil, crushable material and water to give an indication of blast and ground shock mitigation.

Since no good data could be found on the soil depths required to provide earth arching under dynamic conditions, depths were chosen based on static arching requirements. On recovery, it was found that very little damage had occurred. This indicated that the use of static soil data was reasonable.

OBJECTIVES

The DICE THROW event provided the opportunity of testing the subject hardening techniques under dynamic conditions more closely approaching those which would be produced by a nuclear weapon. The specific objectives of this program were to demonstrate the feasibility of achieving significant protection via earth arching under dynamic loads and to determine what soil depth would be required to provide adequate arching. In order for the arching to be effective it was also necessary to show that crushable material would supply enough support to prevent chimneying.

It was desired to obtain a spectrum of damage to obtain arching information. Based on the results of the 5 ton test some of the machines were buried at very shallow depths and two of these had no crushable material at all.

The original DICE THROW overpressures of 40, 80 and 200 psi were chosen before the results of the 5 ton test were obtained. Because of the lack of damage at 300 psi in the latter test a 600 psi station was added at DICE THROW partly for the purpose of obtaining a spectrum of damage.

Other objectives were to obtain data on various types and thicknesses of crushable material and on different water tank hardening concepts.

Passive gauges were emplaced to compare relative motions in soil and chips and to determine motion as a function of depth.

Figure 1a, page 5, gives trench locations and lists items emplaced in each trench.

PROCEDURES

Several types of equipment were placed at 600, 200, 80, and 40 psi locations at the DICE THROW site:

1. Four large machines:
   a) A minibike at 600 psi.
   b) An Exactomatic drill grinder at 200 psi (equivalent to the grinder buried at the Boeing Auburn facility).
   c) An electrolytic chip breaker grinder at 80 psi.
   d) The power supply for the electrolytic chip breaker grinder at 40 psi.
2. Sixteen aluminum 6 in. diameter pipes of three different wall thicknesses at 600 psi to permit analytical correlations of observed damage with predicted failure loads.
3. Six electric chain hoists to represent rugged machines.
4. Four varidrives and a vacuum pump to represent medium hard machines.
5. Twenty-two mechanical/electric desk calculators and adding machines to represent soft machines.
6. Five water filled electronic cabinet racks to represent chemical tanks from chemical processing lines.
7. Small items at 600 psi (see below).

(All the machines from the 5 ton test were included in the DICE THROW test.) The layouts of the four overpressure locations are shown in Figures 2 through 5. Examples of hardening techniques used for a grinder and a water tank are illustrated in Figure 6. The protective packaging techniques used for each specimen are listed in Table 1b for overpressures below 600 psi (this overpressure is discussed separately below).

200, 80 and 40 psi

Most test specimens were placed on a foundation of rigid polystyrene foam since, as mentioned before, it is expected that any pre-placed foundation protective material must be rigid to permit normal operation. Either flexible polyurethane or aluminum chips were also placed under some specimens to represent the placement of final protective material to fill voids in machine support stands or legs.

TEST SPECIMENS:

1. MINIBIKE
2. DESK CALCULATOR
3. HAND CALCULATOR
4. POCKET WATCH
5. "GOT A MINUTE" GAME
6. ALUMINUM PIPE BURIED IN CHIPS
7. SET OF PASSIVE GAGES
8. ALUMINUM PIPE BURIED IN SOIL
9. SET OF PASSIVE GAGES

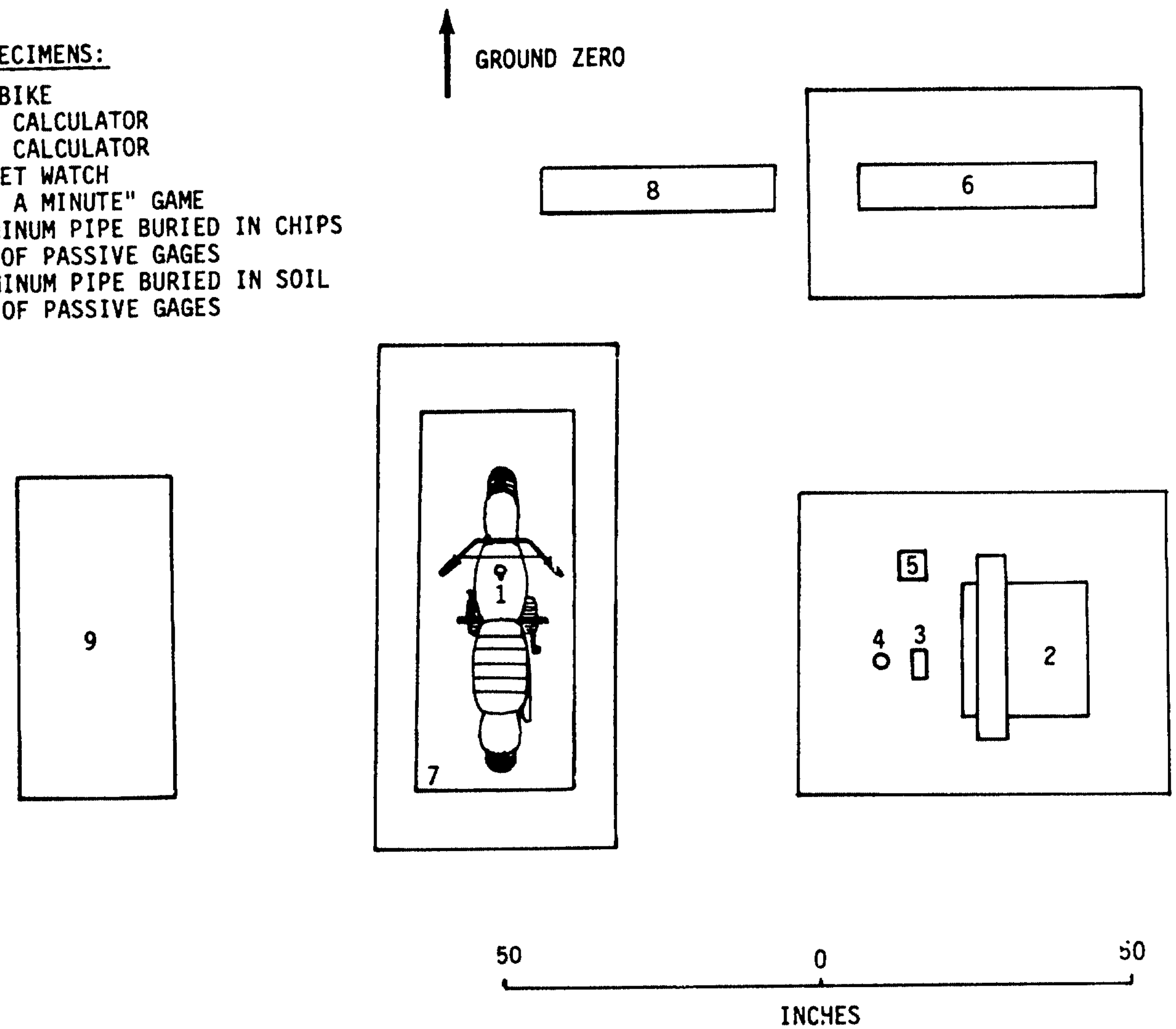


FIGURE 2: 600 PSI, LOWEST LEVEL
FOUR FEET OF EARTH ABOVE CHIPS

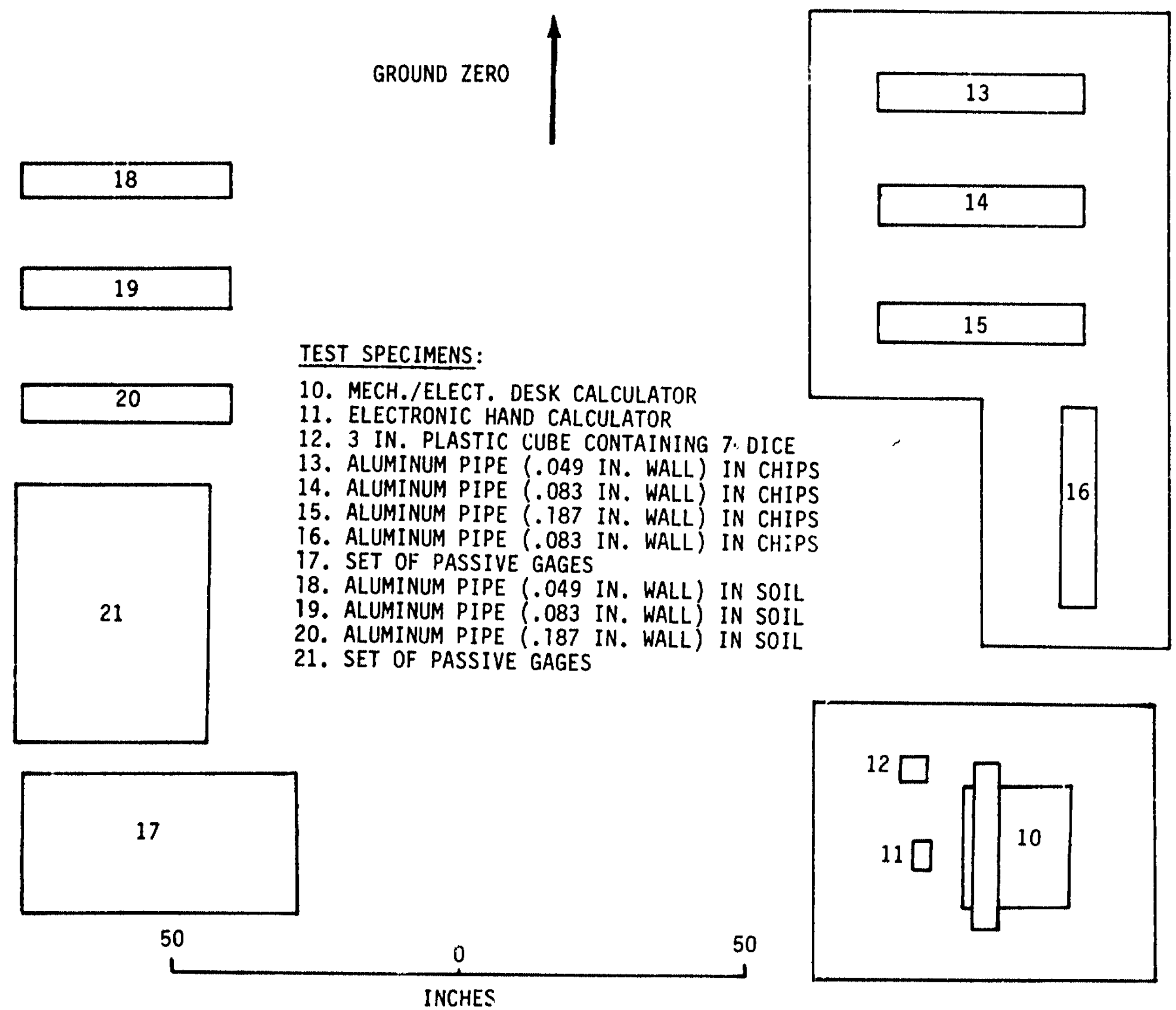
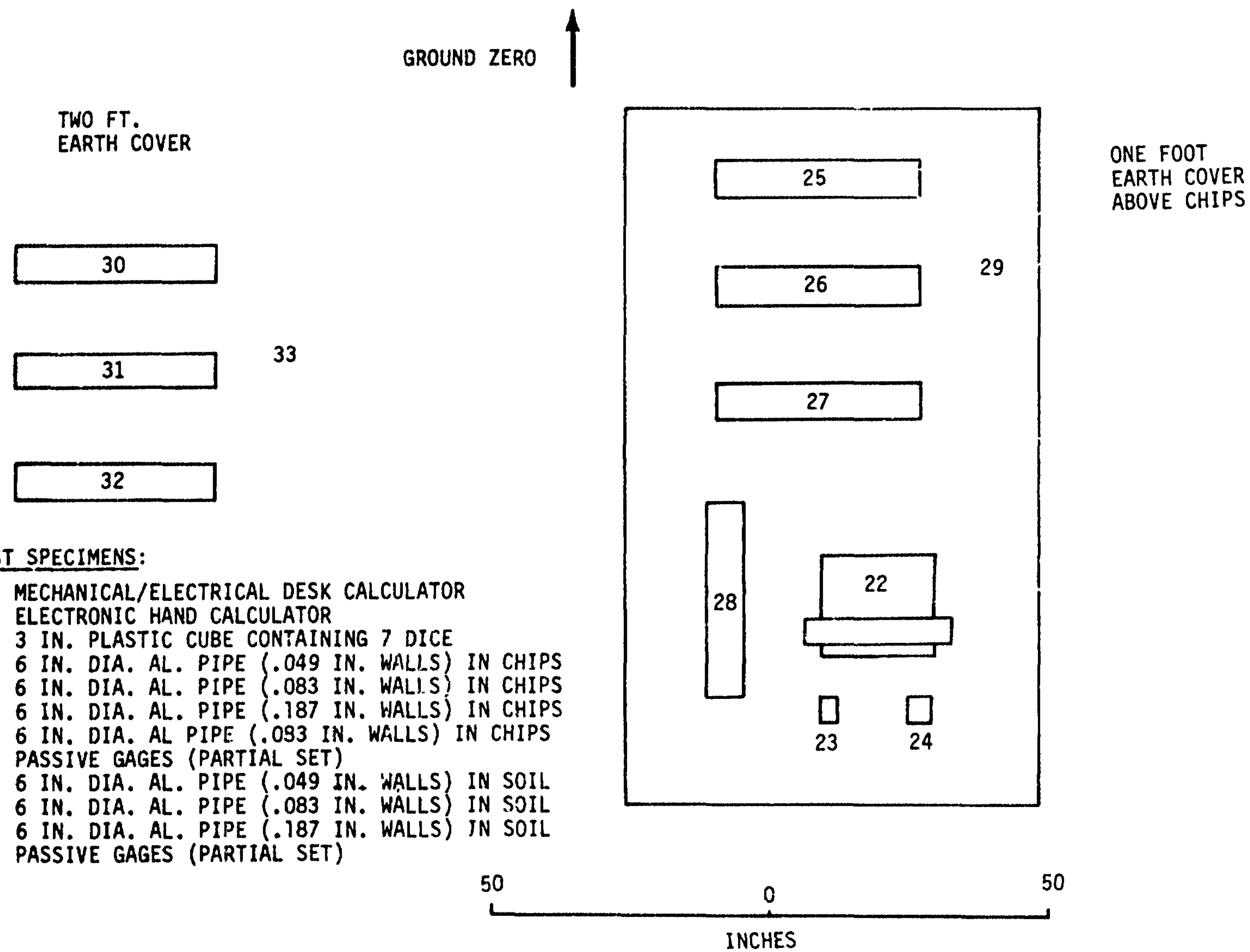


FIGURE 3: 600 PSI, MIDDLE LEVEL
TWO FEET OF EARTH ABOVE CHIPS



TEST SPECIMENS:

22. MECHANICAL/ELECTRICAL DESK CALCULATOR
23. ELECTRONIC HAND CALCULATOR
24. 3 IN. PLASTIC CUBE CONTAINING 7 DICE
25. 6 IN. DIA. AL. PIPE (.049 IN. WALLS) IN CHIPS
26. 6 IN. DIA. AL. PIPE (.083 IN. WALLS) IN CHIPS
27. 6 IN. DIA. AL. PIPE (.187 IN. WALLS) IN CHIPS
28. 6 IN. DIA. AL PIPE (.093 IN. WALLS) IN CHIPS
29. PASSIVE GAGES (PARTIAL SET)
30. 6 IN. DIA. AL. PIPE (.049 IN. WALLS) IN SOIL
31. 6 IN. DIA. AL. PIPE (.083 IN. WALLS) IN SOIL
32. 6 IN. DIA. AL. PIPE (.187 IN. WALLS) IN SOIL
33. PASSIVE GAGES (PARTIAL SET)

FIGURE 4: 600 PSI, TOP LEVEL

ONE FOOT OF EARTH ABOVE CHIPS

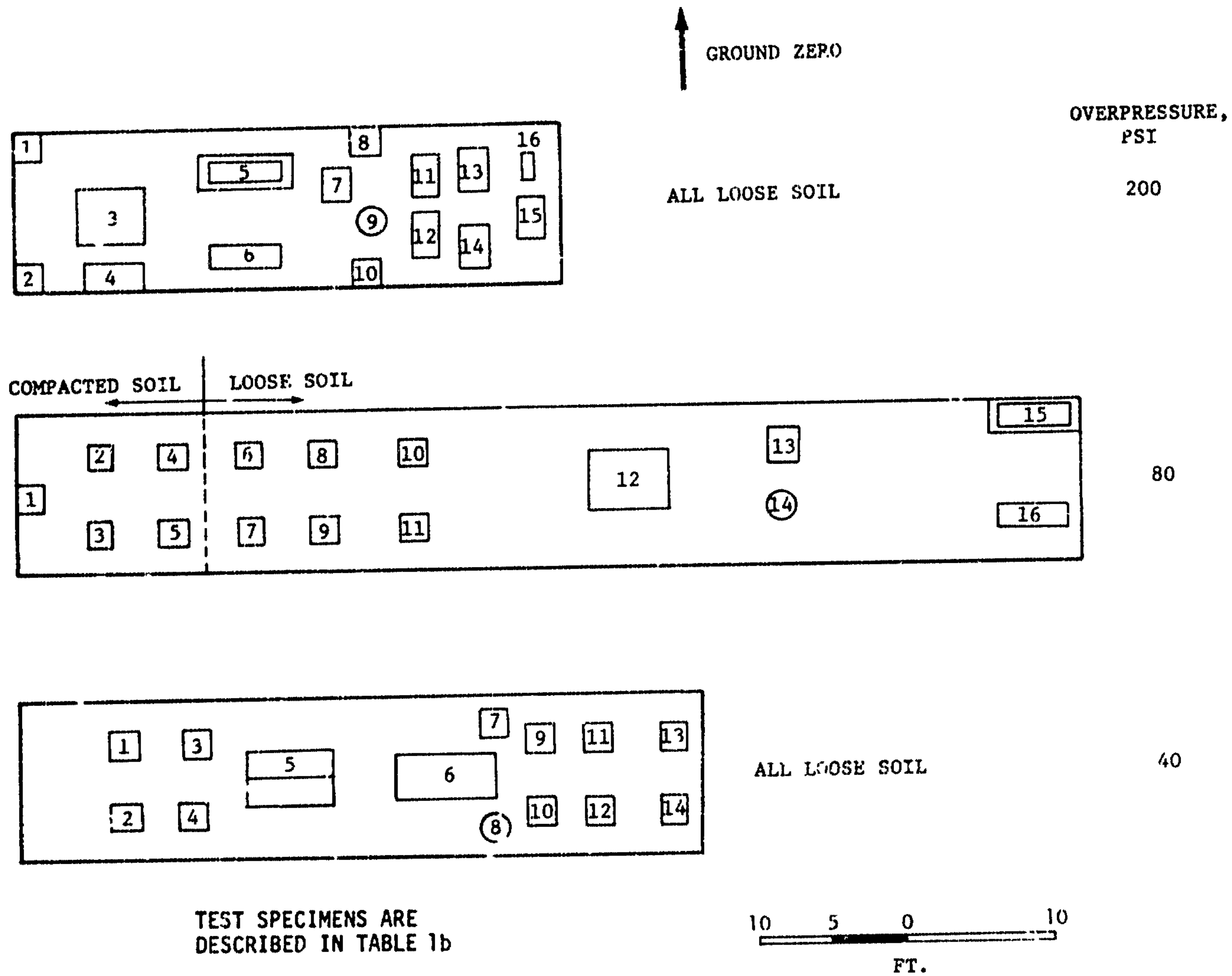


FIGURE 5: EMPLACEMENT OF ITEMS AT 200, 80 AND 40 PSI
(KEYED TO TABLE 1b)

80 PSI

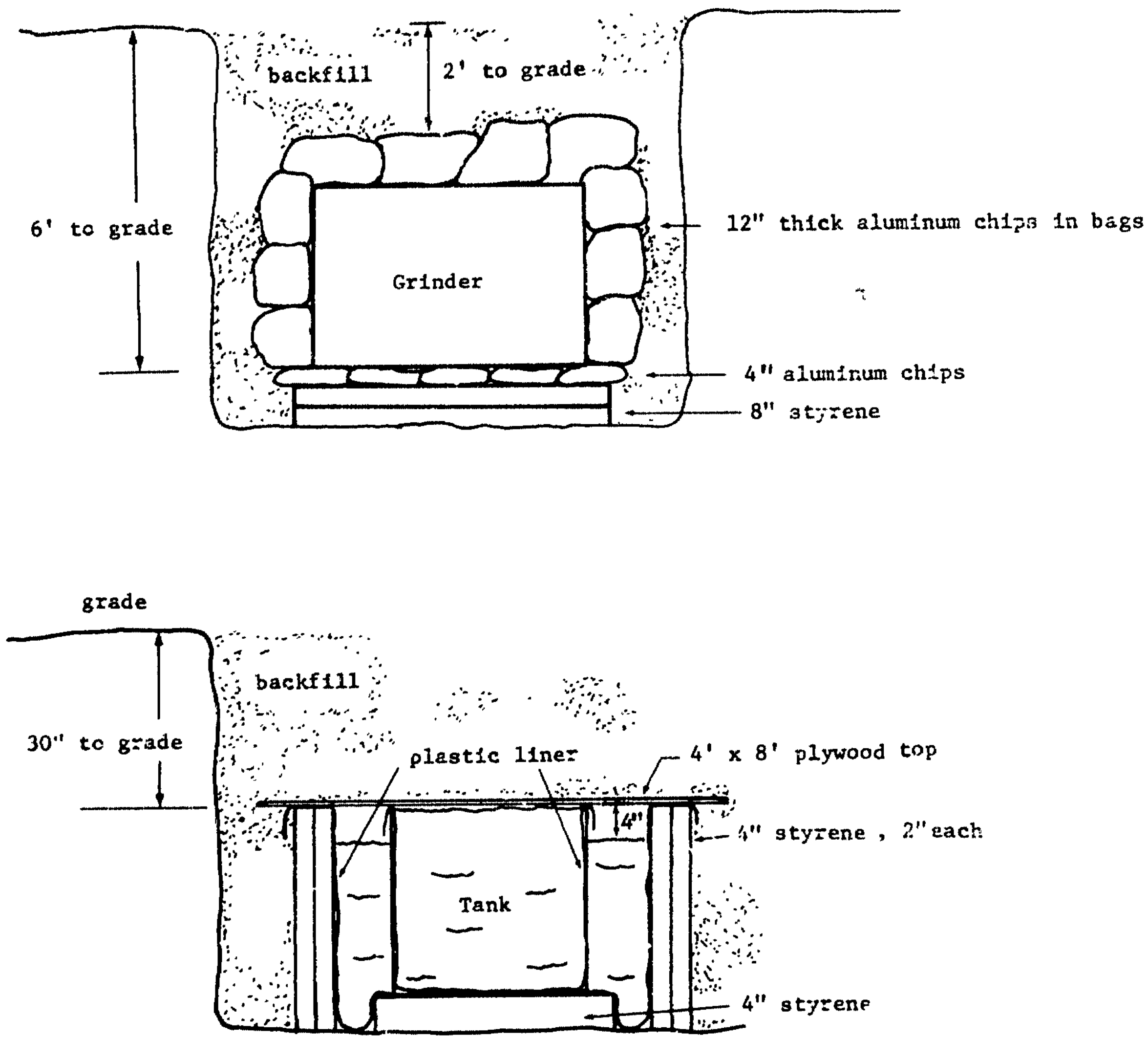


FIGURE 6: TYPICAL EMPLACEMENT DETAILS, LARGE GRINDER AND DOUBLE WALLED TANK AT 80 PSI

All machines (with a few exceptions) were then surrounded on all sides and on top by a layer of aluminum chips. Past experience on static tests and on the 5 ton TNT shot discussed in the last section had shown that placing the aluminum chips in plastic bags greatly facilitated handling and post shot recovery of specimens.

Simulated chemical tanks (about 2 ft. x 2 ft. x 6 ft.) were placed on polystyrene foundations to represent preplaced protective foundations. One set of tanks at each overpressure below 600 psi was then covered directly with soil. At 80 psi and 200 psi a second set of tanks was enclosed in a larger water tank (about 6" space between the smaller and larger tank) with low strength polystyrene walls. This was done to simulate a tank surrounded by a water-filled pit which is typical of many chemical processing lines where the individual tanks are located in a trench or pit which could be dammed with plastic sheets filled with water.

Earth backfill was mostly by front end loader with little tamping to represent typical expedient backfill procedures. One set of four small machines at 80 psi were carefully backfilled with moistened and mechanically tamped earth. A similar set of four machines at the same location were backfilled with the usual loose dry earth. Any differences in response would help determine the importance of backfill procedures.

Two calculators at 80 psi and one at 200 psi were placed directly in the earth backfill with no protective mat al except a plastic bag to prevent entry of dirt.

Most of the specimens were placed at depths where arching of the soil above the protective material was expected to provide protection from the blast wave. However, at the 200 psi station a set of mechanical/electrical calculators were placed at one foot increments at depths from 5 feet to only 1 foot to assure damage to some specimens and hopefully to determine the minimum depth of cover necessary to assure effective soil arching.

The aluminum chips used were typical spar and skin milling chips with an average density of about fifteen pounds per cubic foot. One specimen at 200 psi was protected by scrap aluminum honeycomb cores with an unusually low density of only five pounds per cubic foot. A comparison specimen (both were vari-drives) was protected by the normal (fifteen pounds per cubic foot) chips.

TABLE 1b EMPLACEMENT DETAILS
OVERPRESSURES BELOW 600 PSI

200 psi

1. VARIDRIVE resting on 4" of styrene and 4" of aluminum chips. Surrounded by 12" of chips (5 lb/ft^3). Seven ft. below grade to bottom of machine.

2. Same as 1 except surrounded by 8" of chips (15 lb/ft^3).

3. ELECTROLYTIC GRINDER (large machine) resting on 8" of styrene and 4" of chips. Surrounded by 12" of chips. Bottom of machine 7 ft. below grade.

4. CALCULATOR placed in chips in plastic garbage can 7 ft. below grade to bottom of garbage can.

5. DOUBLE WALLED TANK Steel tank submerged in plastic lined styrene pool. Plywood cover flush with water surface. Steel tank set on 6" balsa spacers and 4" of styrene. Plywood 46" below grade.

6. SINGLE WALLED STEEL TANK as in 5 but emplanted in soil. Plywood cover flush with water surface. Set on 2" of styrene. Plywood 46" below grade.

7. GAUGES IN SOIL horizontal and vertical scratch and nail gauges plus crush gauges at 1 ft. intervals from surface to 5 ft. below grade.

8. & 10. CHAIN HOISTS set on 4" of styrene and 4" of chips surrounded by 12" of chips (density 15 lb/ft^3 throughout unless otherwise specified). Hoists are 5.5 ft. below grade to bottom of machine.

9. GAUGES IN ALUMINUM CHIPS IN GARBAGE CANS (two cans stacked vertically). Total of four vertical scratch gauges. Horizontal and vertical nail gauges and crush gauges at depths of 2, 4, 6 and 8 ft. below grade.

11. THRU 15. CALCULATORS in chips in garbage cans.

ITEM NO.	Depth below grade to top of can, in.
11	48
12	40
13	32
14	21
15	9

16. UNPROTECTED CALCULATOR packed in soil. Top is 17" below grade.

TABLE 1b (CONTINUED)

80 psi

(ITEMS 1 THROUGH 5 WERE PLACED IN COMPACTED SOIL AND THE REST OF THE ITEMS IN LOOSE SOIL)

1. GAUGES IN SOIL Scratch, nail and crush gauges at 1, 2, 3 and 4 ft. below grade.

2. THRU 9. These are small machines placed on 4" of styrene and 2" of polyurethane and surrounded by chips. Depths are given from grade to the top of the chips (before compression) as well as packing chip thickness.

ITEM NO.	DESCRIPTION	DEPTH, IN.	PACKING CHIP THICKNESS, IN.
2	CALCULATOR	24	6
3	VARIDRIVE	30	6
4	CHAIN HOIST	22	6
5	CALCULATOR	26	12
6	CALCULATOR	26	6
7	CALCULATOR	28	12
8	CHAIN HOIST	22	6
9	VARIDRIVE	23	6

10. & 11. UNPROTECTED CALCULATORS packed in soil. Tops of No. 10 and 11 are 24" and 30" below grade, respectively. (Item 10 is a printing adding machine.)

12. CHIP BREAKER GRINDER (large machine) Placed on 8" of styrene and 4" of chips. Surrounded by 12" of chips. Bottom of machine 6 ft. below grade. Top of chips 2 ft. below grade (before compression).

13. GAUGES IN SOIL Same as item 7 under 200 psi except maximum depth is 4 ft.

14. GAUGES IN ALUMINUM CHIPS IN GARBAGE CANS Same as item 9 under 200 psi.

15. DOUBLE WALLED TANK Water filled steel tank on 4" styrene base surrounded by plastic lined styrene tank. Water level in outer tank 4" below level in inner tank. Plywood cover 30" below grade.

16. SINGLE WALLED TANK Water filled steel tank on 2" styrene base and emplanted in soil. Plywood cover 33" below grade.

TABLE 1b (CONTINUED)

40 psi

1. THRU 4. These small machines are placed on 4" of styrene and 2" of polyurethane. Items 1, 3 and 4 are surrounded by 6" of chips and item 2 by 12". Depths are given from grade to the top of the chips (before compression):

ITEM NO.	DESCRIPTION	DEPTH, IN.
1	CALCULATOR	30
2	CALCULATOR	30
3	CHAIN HOIST	24
4	VACUUM PUMP	26

5. TWO COMPARTMENT STEEL TANK, water filled, placed on 2" of styrene, soil emplanted, plywood cover 31" below grade.

6. POWER SUPPLY FOR ITEM 12, 80 PSI (large, soft item) Placed on 8" of styrene and 4" of chips and surrounded by 1 ft. of chips. Top of chips 27" below grade (before compression).

7. GAUGES IN SOIL Same as item 13 under 80 psi.

8. GAUGES IN ALUMINUM CHIPS IN GARBAGE CANS Same as item 9 under 200 psi.

9. THRU 14. These small machines were placed on 4" of chips and surrounded by 8" of chips. Depths are given from grade to the top of the chips (before compression):

ITEM NO.	DESCRIPTION	DEPTH, IN.
9	CHAIN HOIST	41
10	CALCULATOR	41
11	VARIDRIVE	30
12	CALCULATOR	32
13	ADDING MACHINE	26
14	CALCULATOR	24

Passive gauges were placed in the earth backfill and in aluminum chips at each overpressure location. An aluminum chip column was used at 200, 80 and 40 psi. This column was made by stacking two plastic garbage cans each filled with aluminum chips. Two sizes of wooden scratch gauges were used to measure gross soil movement, the smaller with end plates about 13.5 inches apart and the larger with end plates about 27 inches apart. Figure 7 shows the smaller size scratch gauge and the other passive gauges which were developed. A pressure of about 3 psi is necessary to move the end plates and produce a scratch. Nail penetration gauges were used to measure motion over a smaller range. (These gauges and the crush gauges discussed below were sealed with tape to keep out dirt.) A pressure of 5 to 8 psi is necessary to move the face plate thus driving 4 nails into a balsa block. Maximum motion that can be recorded by this gauge is one inch. Two sizes of thin walled metal cans were used as crush gauges, one gallon flat sided cans (always buried flat), and empty soft drink cans. All of these gauges were used on the 5 ton shot at Holloman. Results indicated they give measurements of relative motion as a function of location (varying depths, varying overpressures, and whether in soil or in aluminum chips). The gauges used do not distinguish between motion from back-filling and settling and from the blast wave, so are only indicators. Figure 8 is a photograph of some of the gauges used.

<u>600 psi</u>

The 600 psi installation requires a special discussion. This installation was a late add-on resulting partly from the unexpected lack of damage in the 5 ton test even at 300 psi. Supplies of some gauges discussed above were exhausted, so some new types of passive gauges had to be used. Also, the only crushable material still available was aluminum chips (15 lb/ft^3).

The major equipment item placed at 600 psi was a small minibike to represent transportation equipment. The minibike possessed pneumatic tires, shock absorbers, transmission, engine, gasoline tank, brakes, frame and padded seat. Thus, most of the items common to transportation equipment except windows, enclosed cab, and batteries were represented. Other equipment items included three mechanical/electrical calculators and three electronic hand calculators. One pocket watch and hollow plastic cubes containing several dice and an hour glass were also placed. The idea behind this was that if the plastic cubes survived, any changes in the dice faces would give an indication of the

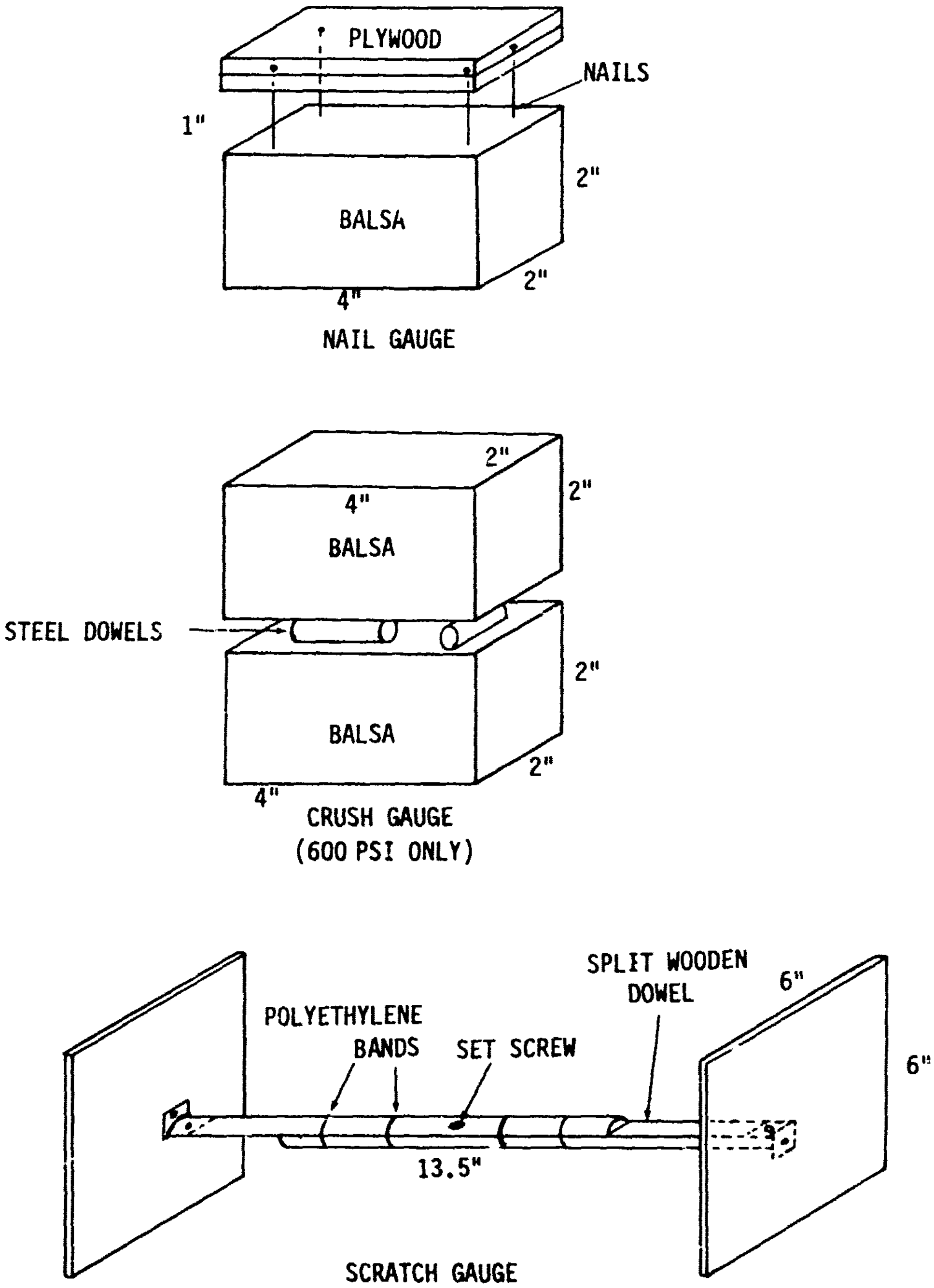


FIGURE 7 : PASSIVE GAUGES USED IN DICE THROW

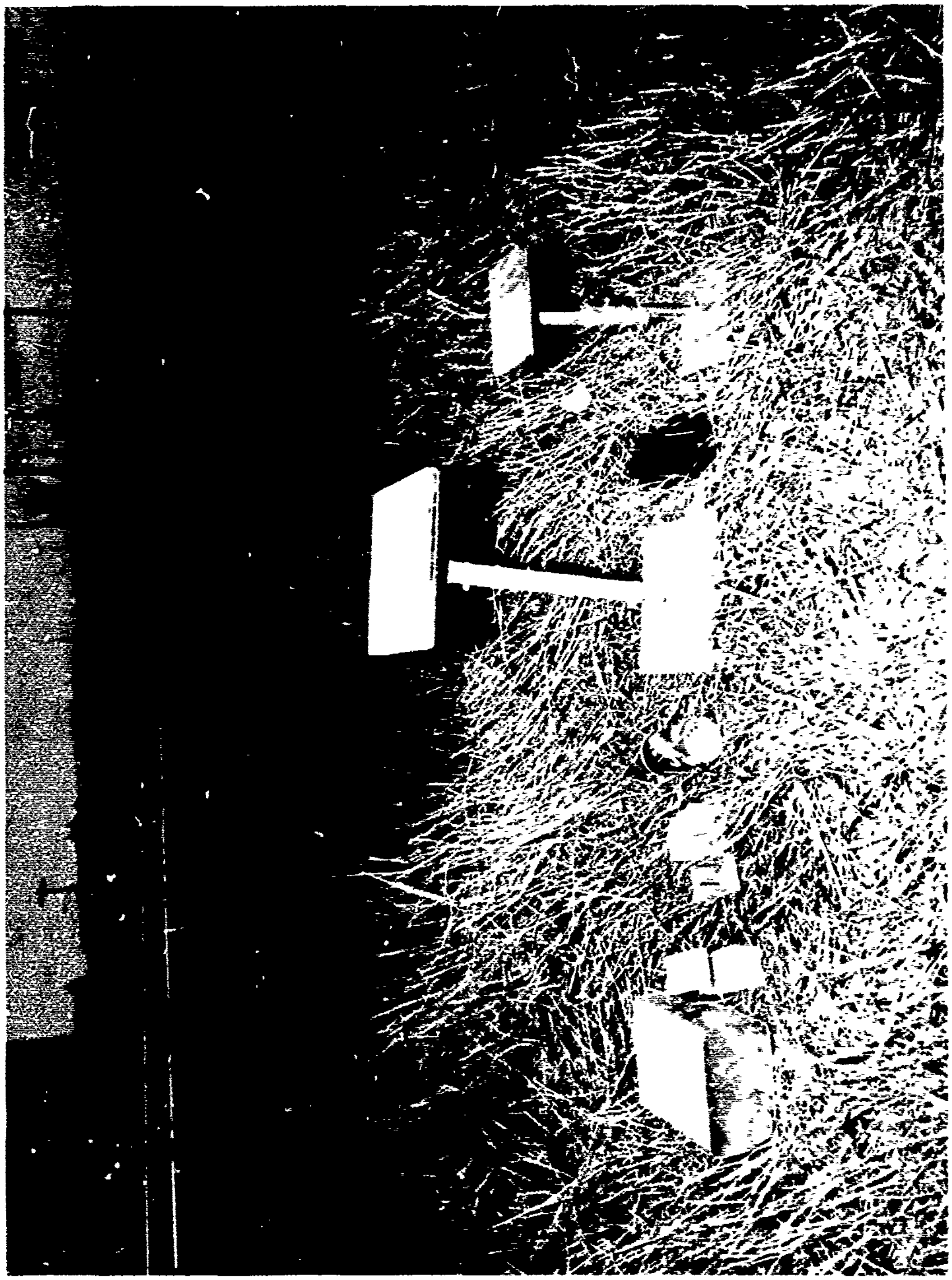


FIGURE 8: GAUGES USED TO RECORD SOIL SETTLING AND COMPACTION DURING TEST

violence of motion experienced.

Thin walled aluminum pipes 6 inches in diameter and 36" long were selected as a simple shape to permit correlation of damage with predicted failure levels. Three wall thicknesses; 49 mil, 83 mil and 187 mil; were used. The pipes were placed at three levels with some covered only with soil and some surrounded by 12 inches of aluminum chips before covering with soil. Spacing between pipes was 12 inches. All pipes were left unfilled. Again a range of damage was desired.

Several types of passive gauges were used.

1. Nail gauges.

2. Pressure imprint gauges (crush gauges). Pressure causes imprints of steel dowel pins on blocks of balsa wood. The depth of the imprint is a measure of pressure up to the strength of balsa (about 1000 psi). (These were in lieu of the scratch gauges used at the lower overpressure sites.)

3. Empty soft drink cans.

4. Ordinary drinking glasses. These gave an indication of forces in soil compared to aluminum chips and at various depths.

5. Sixty watt electric light bulbs. (Same purpose as above.)

Items were placed at three levels as illustrated in Figures 2, 3 and 4 and described in the following list:

<u>Lowest Level</u>

Items placed on 12" of aluminum chips and surrounded on all sides and on top with 12" of aluminum chips. Four feet of earth cover above chips.

1. Minibike with gasoline tank half full and transmission at normal oil level. (For best protection all tanks should be completely full.)

2. Mechanical/electrical calculator.

3. Electronic hand calculator.

4. Pocket watch.

5. Three inch hollow plastic cube containing seven dice.

6. Six inch aluminum pipe, 36" long 49 mil wall thickness tangent to a circle centered at GZ.

7. Set of passive gauges.

Items in soil only. Five feet of earth cover.

8. Six inch diameter aluminum pipe, 36" long 49 mil wall thickness tangent to a circle centered at GZ.

9. Set of passive gauges.

Middle Level

Items placed on 12" of aluminum chips. Surrounded on all sides and on top. Two feet of earth cover above chips.

10. Mechanical/Electrical calculator.

11. Electronic hand calculator.

12. Three inch plastic cube containing seven dice.

13. Six inch aluminum pipe 36" long 49 mil walls tangent to a circle centered at GZ.

14. Six inch aluminum pipe 36" long 83 mil walls tangent to a circle centered at GZ.

15. Six inch aluminum pipe 36" long 187 mil walls tangent to a circle centered at GZ.

16. Six inch aluminum pipe 36" long 83 mil walls with axis toward GZ.

17. Set of passive gauges.

Items in soil only. Three feet of soil cover.

18. Six inch aluminum pipe 36" long 49 mil walls tangent to a circle centered at GZ.

19. Six inch aluminum pipe 36" long 83 mil walls tangent to a circle centered at GZ.

20. Six inch aluminum pipe 36" long 187 mil walls tangent to a circle centered at GZ.

21. Set of passive gauges.

Top Level

Items placed on 12" of aluminum chips, surrounded on all sides and on top by 12" of chips. One foot of earth cover above chips.

22. Mechanical/electrical calculator.
23. Electronic hand calculator.
24. Three inch plastic cube containing seven dice.
25. Six inch aluminum pipe 36" long 49 mil walls tangent to a circle centered at GZ.
26. Six inch aluminum pipe 36" long 83 mil walls tangent to a circle centered at GZ.
27. Six inch aluminum pipe 36" long 187 mil walls tangent to a circle centered at GZ.
28. Six inch aluminum pipe 36" long 83 mil walls with axis toward GZ.
29. Partial set of passive gauges.

Items in soil only. Two feet of earth cover.

30. Six inch aluminum pipe 36" long 49 mil walls tangent to a circle centered at GZ.
31. Six inch aluminum pipe 36" long 83 mil walls tangent to a circle centered at GZ.
32. Six inch aluminum pipe 36" long 187 mil walls tangent to a circle centered at GZ.
33. Partial set of passive gauges.

RESULTS

Complete post shot details of each test item are contained in the Appendix (keyed to the numbering system in Figures 2 through 5). Results are summarized in Tables 2 through 10 In Tables 2 and 3 (machine damage at 600 psi and 200 psi) "undamaged" means either totally undamaged or easily repaired damage (say repairable by one man in a few hours with hand tools. "Repairable" is defined as some higher level of damage (dismantling and some parts replacement might be required). "Irreparable damage" means the item is damaged so extensively that repair would probably not be worthwhile. In most such cases some parts could be cannibalized. Other damage descriptors are used when repairability could not be easily determined. (Machine damage at 80 psi and 40 psi is not tabulated and will be discussed below.)

In Table 4 (6 inch diameter pipes at 600 psi) "undamaged" means a pipe is totally undamaged or only slightly (less than 3/8") out of round. "Flattened" means the pipe is smashed to dimensions like 1" to 3" (minor axis) by 7" to 9" (major axis). A notation such as '1/2" out of round' means both the minor and major axes changed by 1/2" from the original diameter.

Tables 5 through 7 give scratch gauge results at 200, 80 and 40 psi ordered by increasing gauge top depth below post shot grade. In many cases no scratch appeared. This may be due to blast or shock induced torques on the gauge which prevent the set screw from making contact. Solutions in any future test would be to use set screws in both gauge faces, and to turn in these set screws one or two turns beyond grazing contact.

Finally, Tables 8 through 10 give vertical nail gauge readings and results for other gauges.

All nail gauges were originally set at one inch. On recovery the spacings at all four corners were recorded (see Appendix). It was found that very little motion occurred in the horizontal gauges (either radial or tangential). (The smallest reading on any gauge corner was 0.8" while most readings were above 0.95".) Therefore, only the vertical gauge readings (averages of the four corner readings) are given in Table 8 .

Only three of the twelve crush gauges emplaced at 600 psi showed significant indentations. These were the vertical gauges emplaced in soil. The top, middle and lower gauges indicated pressures on the order of 35, 15 and 50 psi, respectively.

TABLE 2 MACHINE DAMAGE AT 600 PSI

ITEM NUMBER LOWEST LEVEL	ITEM	DAMAGE DESCRIPTION
1.	MINIBIKE	UNDAMAGED[1]
2.	DESK CALCULATOR	REPAIRABLE[2]
3.	HAND CALCULATOR	UNDAMAGED
4.	POCKET WATCH	UNDAMAGED
5.	"GOT-A-MINUTE" GAME	UNDAMAGED[4]
MIDDLE LEVEL		
10.	DESK CALCULATOR	IRREPARABLE[3]
11.	HAND CALCULATOR	UNDAMAGED
12.	"GOT-A-MINUTE" GAME	UNDAMAGED[4]
TOP LEVEL		
22.	DESK CALCULATOR	IRREPARABLE
23.	HAND CALCULATOR	NOT SMASHED, BUT DID NOT WORK
24.	"GOT-A-MINUTE" GAME	SMASHED

[1] Undamaged means totally undamaged or easily repaired damage.
[2] Repairable means one man can repair damage in a few hours with hand tools.
[3] Irreparable means damage so extensive that repair is not worthwhile.
[4] Dice scrambled.

TABLE 3 MACHINE DAMAGE AT 200 PSI

ITEM NUMBER	ITEM	DAMAGE DESCRIPTION*
1.	VARIDRIVE	UNDAMAGED
2.	VARIDRIVE	UNDAMAGED
3.	LARGE GRINDER	UNDAMAGED
4.	DESK CALCULATOR	REPAIRABLE
5.	DOUBLE WALLED TANK	REPAIRABLE
6.	SINGLE WALLED TANK	REPAIRABLE
8.	CHAIN HOIST	UNDAMAGED
10.	CHAIN HOIST	UNDAMAGED
11.	DESK CALCULATOR (5')**	IRREPARABLE
12.	DESK CALCULATOR (4')	IRREPARABLE
13.	DESK CALCULATOR (3')	IRREPARABLE
14.	DESK CALCULATOR (2')	REPAIRABLE
15.	DESK CALCULATOR (1')	IRREPARABLE
16.	UNPROTECTED DESK CALCULATOR (1')	IRREPARABLE

* Same definitions as in Table

**Approximate depth of top of calculator below preshot grade.

TABLE 4 PIPE DAMAGE AT 600 PSI

ITEM NUMBER	BURIED IN	WALL THICKNESS, MILS	DAMAGE DESCRIPTION
LOWEST LEVEL			
6.	CHIPS	49	1/2" OUT OF ROUND
8.	SOIL	49	1/2" OUT OF ROUND
MIDDLE LEVEL			
13.	CHIPS	49	ONE END FLATTENED[1] OTHER END UNDAMAGED[2]
14.	CHIPS	83	ONE END FLATTENED, OTHER END UNDAMAGED
15.	CHIPS	187	ONE END 1/2" OUT OF ROUND, OTHER END UNDAMAGED
16.	CHIPS	83	ONE END FLATTENED, OTHER END OUT OF ROUND 3/8"
18.	SOIL	49	ONE END OUT OF ROUND 3/8", OTHER END UNDAMAGED
19.	SOIL	83	OUT OF ROUND 3/8"
20.	SOIL	187	UNDAMAGED
TOP LEVEL			
25.	CHIPS	49	FLATTENED
26.	CHIPS	83	FLATTENED
27.	CHIPS	187	ENDS OUT OF ROUND ABOUT 2" AND ABOUT 1/2"
28.	CHIPS	83	ONE END OUT OF ROUND 1", OTHER END FLATTENED
30.	SOIL	49	OUT OF ROUND ABOUT 1"
31.	SOIL	83	OUT OF ROUND ABOUT 1"
32.	SOIL	187	UNDAMAGED

[1] Flattened means pipe smashed to dimensions like 1" to 3" (minor axis) by 7" to 9" (major axis).

[2] Undamaged means out of round less than 3/8".

TABLE 5 200 PSI SCRATCH GAUGE READINGS

ITEM NUMBER	GAUGE TOP DEPTH BELOW POST SHOT GRADE, IN.	PERM. DISPLACEMENT, IN.	MAX SCRATCH LENGTH, IN.
LARGE VERTICAL GAUGES IN SOIL ABOVE MACHINES			
1	18	0.33	2.48
10	20	1.06	3.25
5	25	2.55	4.15
6	25	1.56	NONE
2	29	1.88	NONE
3	31	2.00	NONE
7	GAUGES IN SOIL		
SMALL VERTICAL GAUGES			
a.	6	1.37	1.86
b.	18	1.10	1.70
c.	28	1.20	2.05
d.	40	1.36	2.40
e.	51	1.22	1.92
LARGE HORIZONTAL GAUGES			
f.	7	0.10	0.45
g.	22	0.15	0.27
h.	35	0.03	0.42
i.	44	0.42	0.80
j.	53	0.00	0.10
9	SMALL VERTICAL GAUGES IN CHIPS		
a.	19	FULLY COLLAPSED (DAMAGED IN RECOVERY?)	
b.	29	1.35	2.30
c.	44	0.93	2.30
d.	56	0.95	2.02

TABLE 6

80 PSI SCRATCH GAUGE READINGS

ITEM NUMBER	GAUGE TOP DEPTH BELOW POST SHOT GRADE, IN.	PERM. DISPLACEMENT, IN.	MAX SCRATCH LENGTH, IN.
VERTICAL GAUGES IN SOIL ABOVE MACHINES (ALL GAUGES ARE SMALL EXCEPT THOSE ON ITEMS 15 AND 16)			
15 (LARGE GAUGE)	9	1.56	2.25
16 (LARGE GAUGE)	10	1.62	2.62
6	12	0.58	0.82
8	12	0.44	0.63
2 (COMPACT SOIL)	13	0.62	0.95
7	15	0.82	1.18
11	16	0.87	1.10
5 (COMPACT SOIL)	17	0.85	1.18
9	17	0.50	0.75
3 (COMPACT SOIL)	18	0.62	1.18
10	27	0.95	0.95
1. SMALL GAUGES IN COMPACT SOIL			
a. VERTICAL	22	1.56	NONE
b. HORIZONTAL	20	0.87	0.90
13. LARGE GAUGES IN LOOSE SOIL			
VERTICAL GAUGES			
a.	20	1.57	2.56
b.	43	2.00	2.70
HORIZONTAL GAUGES			
c.	32	0.07	0.40
d.	37	0.00	0.25
e.	52	0.15	0.32
14. SMALL VERTICAL GAUGES IN CHIPS			
a.	16	1.24	2.18
b.	30	1.03	1.64
c.	44	0.82	1.80
d.	56	1.13	2.15

TABLE 7

40 PSI SCRATCH GAUGE READINGS

ITEM NUMBER	GAUGE TOP DEPTH BELOW POST SHOT GRADE, IN.	PERM. DIS-PLACEMENT, IN.	MAX SCRATCH LENGTH, IN.
SMALL VERTICAL GAUGES IN SOIL ABOVE MACHINES (LARGE GAUGE ABOVE ITEM 10 LEFT OUT BECAUSE POST SHOT DEPTH NOT MEASURED - - SEE APPENDIX FOR READINGS)			
6.	14	0.30	0.70
2.	15	0.53	0.65
3.	15	0.50	0.60
4.	17	0.43	0.74
14*	18	0.55	0.60
13	19.5	0.90	1.56
5a.	20	0.83	1.25
5b.	20	1.10	1.40
11.	22	0.23	0.55
12.	25	0.55	0.75
7. VERTICAL GAUGES IN SOIL			
LARGE GAUGES			
a.	4	2.42	NONE
b.	19	3.00	1.20
SMALL GAUGE			
c.	24.5	0.90	1.55
8. SMALL VERTICAL GAUGES IN CHIPS			
a.	17	1.15	1.73
b.	29	1.08	1.58
c.	42	0.65	1.12
d.	54	1.00	1.48

*Two sets of data in field notes. See Appendix.

TABLE 8

AVERAGE VERTICAL NAIL GAUGE READINGS

OVER-PRESSURE	GAUGES IN SOIL		GAUGES IN CHIPS	
	DEPTH BELOW POST-SHOT GRADE, IN.	READING, IN.	DEPTH BELOW POST-SHOT GRADE, IN.	READING, IN.
600 PSI	35	0.58	35	0.00*
	46	0.31		
	56	0.62	56	0.00*
	90	0.39	88	0.22
200 PSI	11	0.59		
	26	0.47	26	0.85
	37	0.45	38	0.80
			53	0.78
	61	0.37	65	0.66
80 PSI	7 COMPACT SOIL	0.31		
	23 "	0.54	25	0.93
	32 "	0.56		
	36 LOOSE SOIL	0.64	37	0.79
	41 " "	0.82		
	54 " "	0.58	52	0.95
	66 " "	0.53	65	0.83
40 PSI	18	0.51	25	0.98
			36	1.00**
			51	0.98
			64	1.00**

* Gauge "bottomed out"

** No movement

TABLE 9

MISCELLANEOUS GAUGES AT 600 PSI

		GAUGES IN SOIL	GAUGES IN CHIPS
LOWEST LEVEL			
LIGHT BULBS:	VERTICAL	SMASHED	UNDAMAGED
	RADIAL	"	SMASHED
	TANGENTIAL	"	"
WATER GLASSES:	VERTICAL	UNDAMAGED	UNDAMAGED
	RADIAL	SMASHED	"
	TANGENTIAL	"	"
12 OZ. CANS:	VERTICAL	1/2" CRINKLES	ENDS CRUSHED IN 3/8"
	RADIAL	3/4" CRINKLES	1/2" DENTS
	TANGENTIAL	3/4" CRINKLES	1/4" DENTS
MIDDLE LEVEL			
LIGHT BULBS:	VERTICAL	SMASHED	SMASHED
	RADIAL	"	"
	TANGENTIAL	"	UNDAMAGED
WATER GLASSES:	VERTICAL	UNDAMAGED	UNDAMAGED
	RADIAL	SMASHED	"
	TANGENTIAL	"	"
12 OZ. CANS:	VERTICAL	1/2" CRINKLES	1" DENTS
	RADIAL	3/8" CRINKLES AND FLATS	1/2" DENTS
	TANGENTIAL	" " " "	1/2" CRINKLES
TOP LEVEL			
WATER GLASS		SMASHED	SMASHED
12 OZ. CANS:	VERTICAL	COLUMN FAILURE (NOT FLAT)	SMASHED FLAT
	RADIAL	SMASHED	SMASHED TO 1/2 VOLUME
	TAGENTIAL	"	SMASHED FLAT

TABLE 10

MISCELLANEOUS GAUGES AT 200, 80 AND 40 PSI

OVER-PRESSURE	ITEM NUMBER	DEPTH BELOW POST SHOT GRADE, IN.	ITEM	DAMAGE DESCRIPTION
200 PSI	7. GAUGES IN SOIL			
	a.	13	ONE GAL.CAN	0.3" DENTS
	b.	25	" " "	0.3" DENTS*
	c.	36	" " "	0.3" DENTS
	d.	50	" " "	0.5" DENTS
	e.	59	" " "	0.4" DENTS
	9. GAUGES IN CHIPS			
	a.	26	12 OZ CAN	0.3" BOTTOM CRUSHED
	b.	53	" " "	0.4" TOP AND BOTTOM CRUSHED
80 PSI	1. GAUGES IN COMPACT SOIL			
	a.	7	ONE GAL.CAN	ABOUT 1" DENTS ALL AROUND
	b.	23	" " "	" " " " "
	c.	32	" " "	" " " " "
	13. GAUGES IN LOOSE SOIL			
	a.	36	ONE GAL.CAN	ABOUT 0.4" DENTS
	b.	41	" " "	" " "
	c.	52	" " "	" 0.5" "
	d.	68	" " "	" " "
	14. GAUGES IN CHIPS			
	a.	25	12 OZ CAN	UNDAMAGED
	b.	52	" " "	"
40 PSI	7. GAUGES IN SOIL			
	a.	18	ONE GAL CAN	DAMAGED ON RECOVERY
	b.	24	" " "	ABOUT 0.75" DENTS
	c.	40	" " "	" 0.5" "
	8. GAUGES IN CHIPS			
	a.	25	12 OZ.CAN	UNDAMAGED
	b.	51	" " "	"

*Less damage than item 7a

INTERPRETATION OF RESULTS

1. MACHINES

The tests showed that a combination of crushable material and earth arching can protect quite soft machines against very high overpressures (up to 600 psi). A minibike survived* at 600 psi (see Figures 9 and 10) and full scale industrial machines survived at 200, 80 and 40 psi (see Figures 11 and 12 for example). Numerous smaller machines also survived at all these overpressures. Since a spectrum of damage was desired some items such as the calculators in Figure 13 were purposely buried with insufficient arching. The three desk calculators buried at 600 psi showed progressively less damage with increasing depth. The arch failed as expected at the shallowest depth (Figure 14) and everything at this level was damaged. Interestingly the hand calculator and the very soft "Got-A-Minute" game survived at the middle level even though the desk calculator was damaged. Judging from crush gauge readings (see Gauge section below) the repairable damage to the lowest desk calculator was caused by ground shock rather than arch failure.

At 200 psi (Table 3) all desk calculators were packed in chips in garbage cans. Not enough rattle space was obtained between the ends of the carriages and the sides of the garbage cans to provide protection. All of these calculators were damaged with only two (items 4 and 14) deemed to be repairable. Item 4 was placed in the bottom of the 7 ft. trench. The other calculators were placed at various depths down a ramp at one end of the trench. With one exception, item 14, there was not enough spacing between cans to provide adequate arching. The result was a "channel of destruction". Item 14 was placed somewhat to one side of this channel, so received less damage. Figure 13 shows the two shallowest calculators at 200 psi (items 15 and 16). The unprotected calculators on the right clearly received more damage than the left calculator which was in chips.

Varidrive 1 was placed in 12" of lightweight chips and varidrive 2 in 8" of the usual heavier chips. The fact that varidrive 2 received very slight damage could mean that rattle space is more important than crushable material density for the particular conditions at this site.

*In this section survival is defined as no damage or only "cosmetic" damage.

FIGURE 9: DESK AND HAND CALCULATORS, MINIBIKE AND PIPES TO BE EMPLACED AT 600 PSI

FIGURE 10: MINIBIKE BEING DRIVEN MINUTES AFTER RECOVERY

FIGURE 11: GRINDER BEING EMPLACED AT 200 PSI

FIGURE 12: POST-SHOT VIEW OF GRINDER AT 200 PSI -- ESSENTIALLY UNDAMAGED

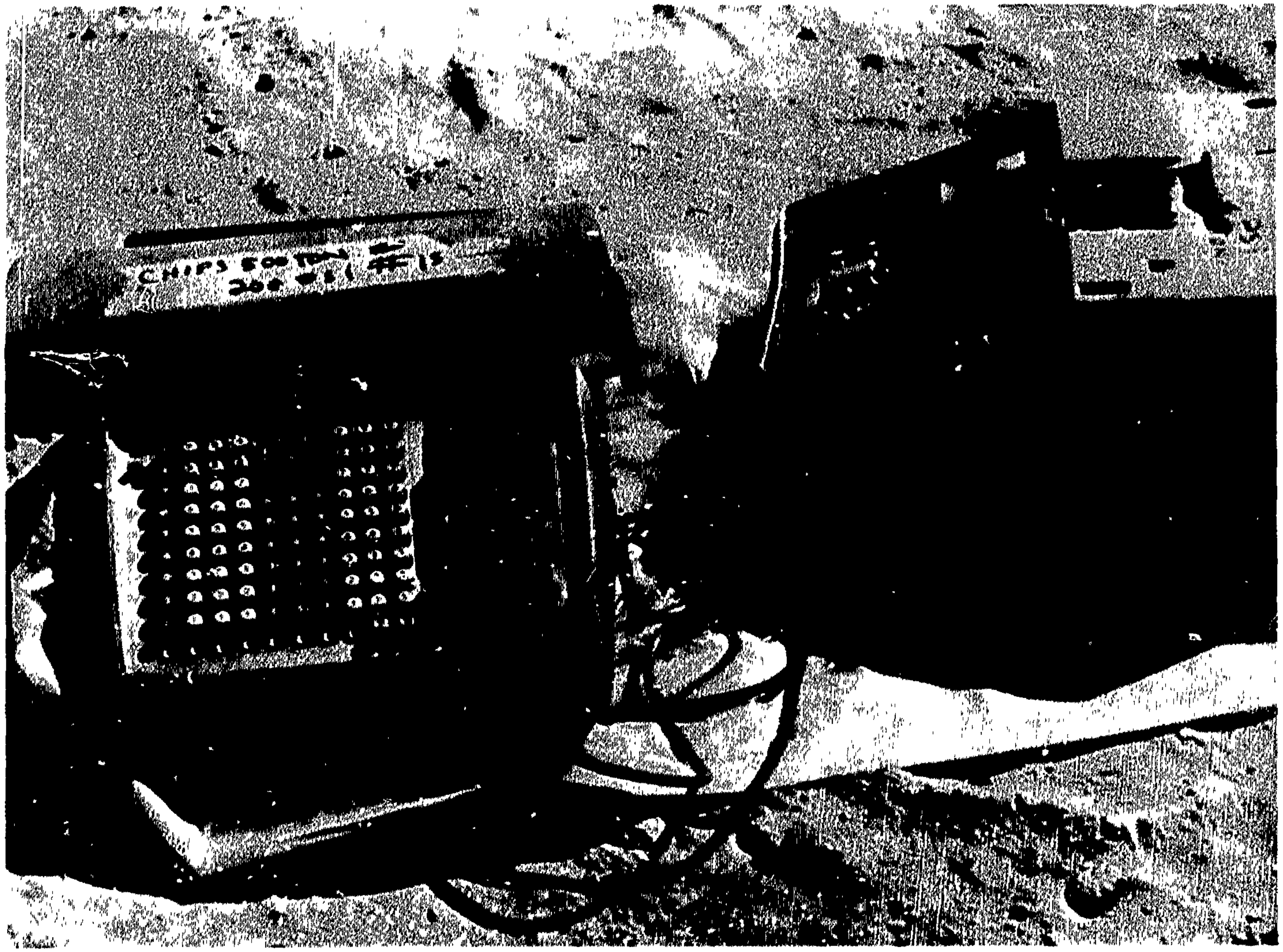


FIGURE 13: PROTECTIVE EFFECTS OF USING METAL CHIPS. CALCULATOR ON LEFT WAS PROTECTED WITH CHIPS. CALCULATOR ON RIGHT WAS NOT.

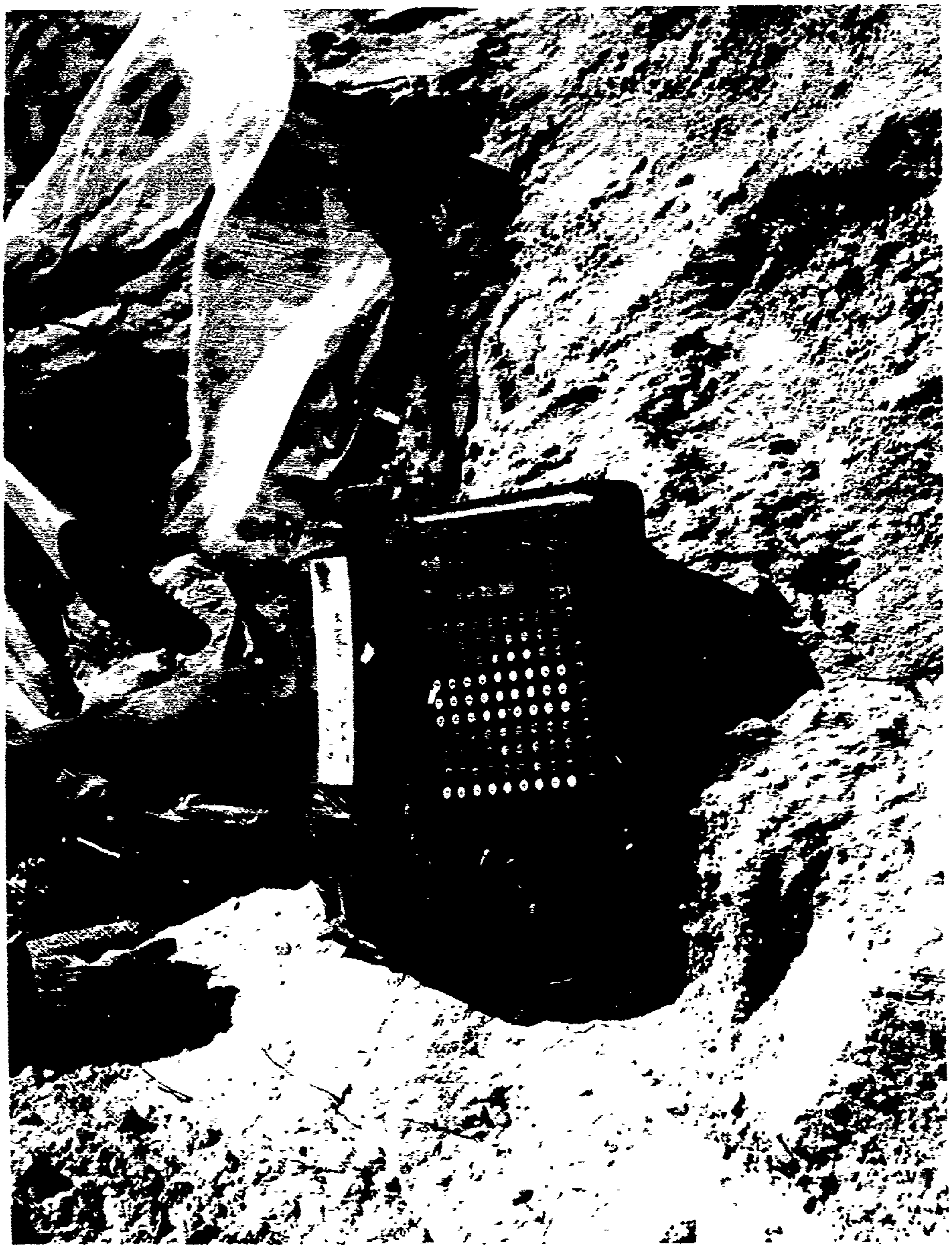


FIGURE 14: CALCULATOR FROM TOP LEVEL AT 600 PSI -- IRREPARABLE DAMAGE

The only major damage at 80 psi was expected irreparable damage to unprotected desk calculators 10 and 11 (tops 24" and 30" below preshot grade respectively). Note that even 6" of chips protected other calculators at this overpressure from major damage. Both compacted and loose soil gave adequate protection.

At 40 psi only desk calculator 14 received major damage. This was unexpected based on 80 psi results, since this calculator was surrounded with crushable material. It was the shallowest calculator (24" of soil). Other calculators (items 10, 12 and 13) survived in repairable condition with the same crushable material characteristics, but more soil cover.

2. TANKS

Most of the equipment tested in this program came from stocks which were surplus to Boeing Co. needs. In every case except the process tank simulations, acceptable items were found. For the tank simulations the only items available which remotely resembled tanks were electronic racks. These had no backs (except the double tank at 40 psi) so could only be used to simulate the four sides of a tank after being lined with sheet plastic. Double walled tanks required field improvisation since only styrene sheets and tape were available to construct the outer tank (also lined with sheet plastic).

These simulated tanks were not too satisfactory from several standpoints. The sharp rack edges tended to cut the sheet plastic. The outer tank walls were too weak and flexible. Finally in some cases the blast wave caused tension tears in the sheet plastic in the tank corners.

Despite these problems all of the tanks received damage which would be repairable. (Five ton test results on much smaller tanks indicated that if rigid waterproof tanks had been available, much less damage might have resulted.) It was not clear from the results whether single or double walled tanks are preferable. Figures 15 and 16 show the single walled tank at 80 psi (item 16) before and after the shot.

3. PIPES (600 psi)

The flat beds of chips at both the top and middle levels were too broad to sustain an arch. As a result the pipes in chips at these levels

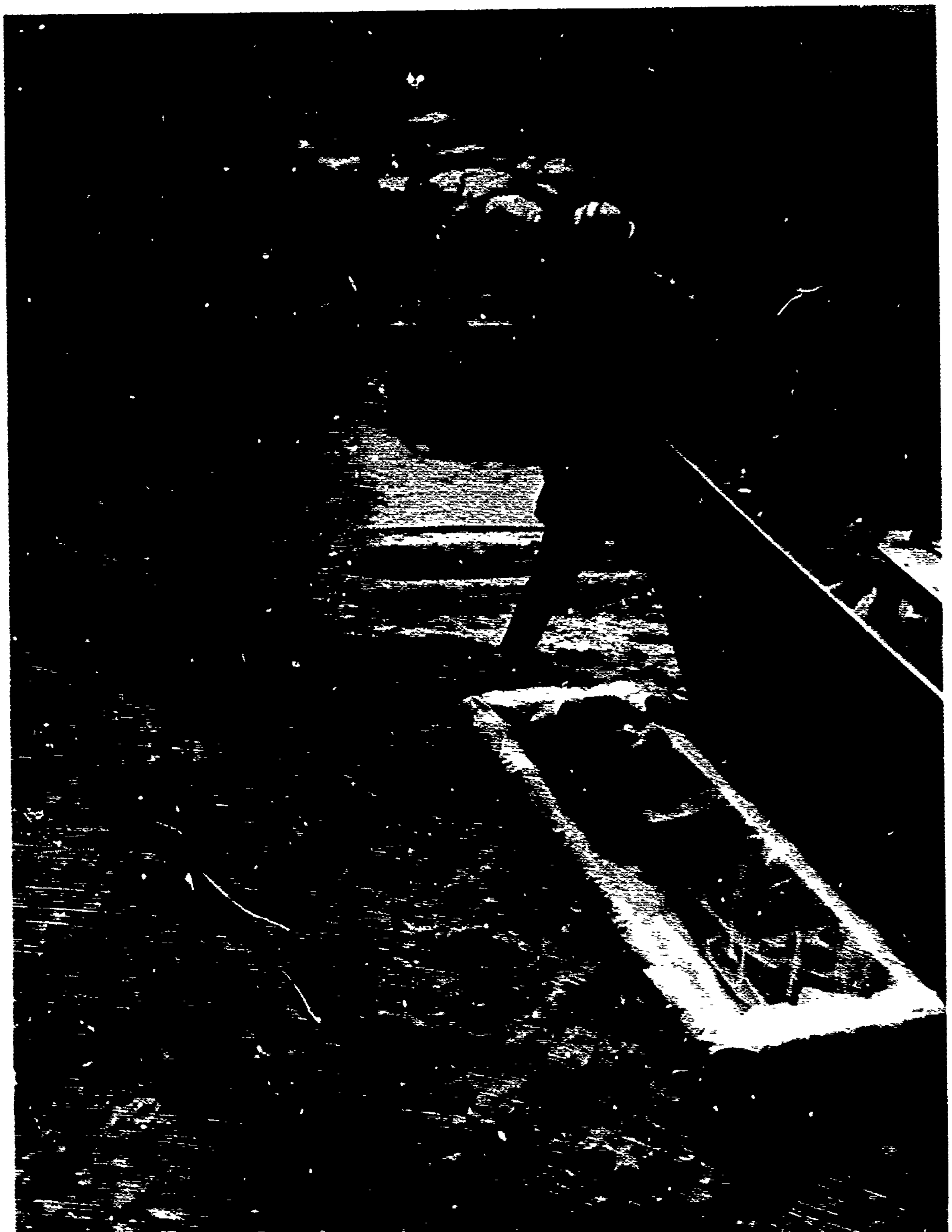


FIGURE 15: SINGLE WALLED TANK BEING EMPLACED AT 80 PSI (LARGE GRINDER AND SMALL MACHINES IN BACKGROUND)

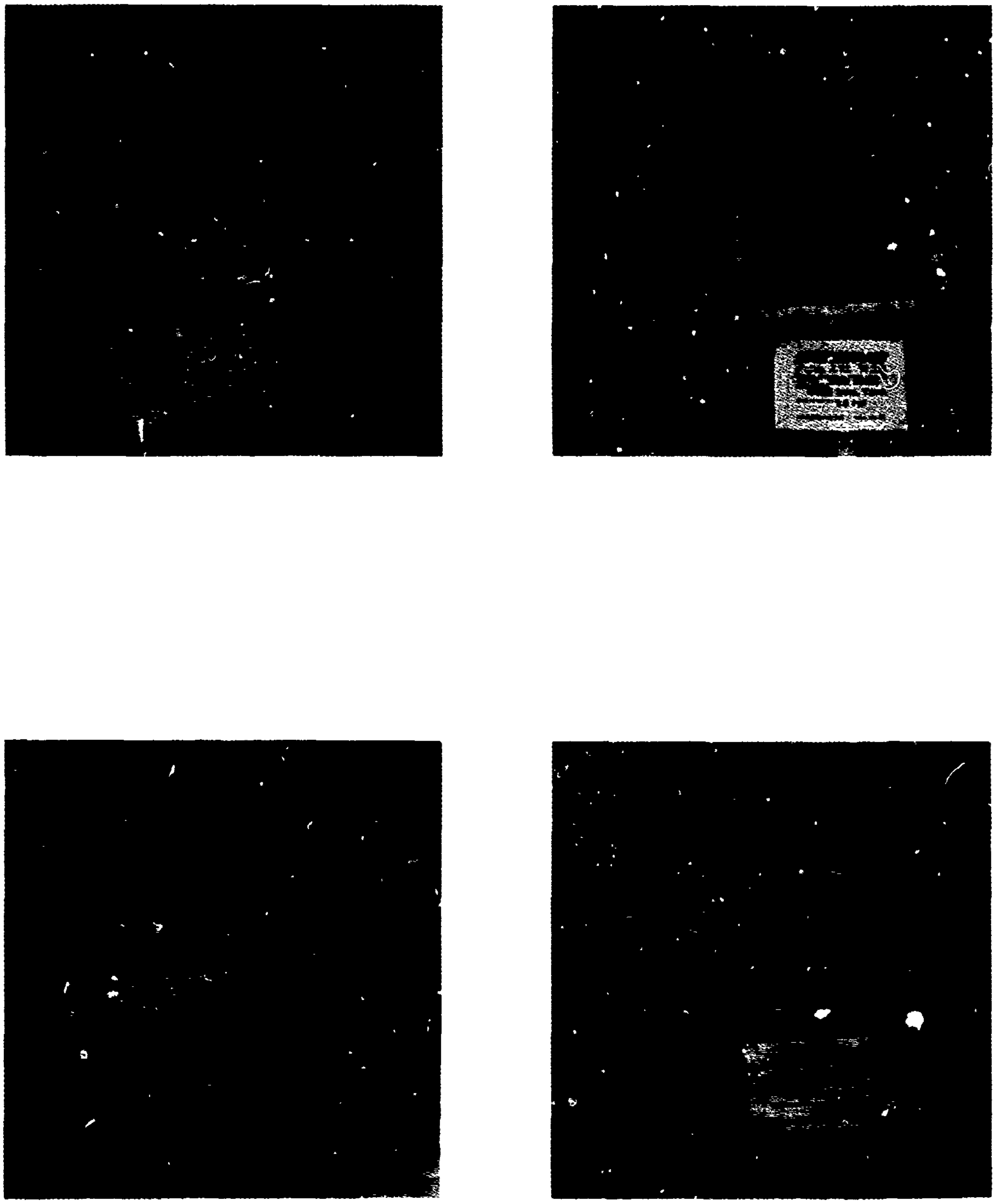


FIGURE 16: POST-SHOT VIEWS OF ELECTRONIC RACK TANK AT 80 PSI

sustained more damage than those in soil. (Pipes at the lowest level sustained the same damage in chips and soil.) Some damage details are given in Table 4. However, pipe motions and specific damage modes were extremely complex. Any attempt at an analytic treatment should be based on detailed data in the Appendix. Figure 17 shows damage to the pipes at the top level at 600 psi.

4. GAUGES

a. Crush Gauges

All gauge results except those for the 600 psi crush gauges are summarized in Tables 5 through 10. The crush gauge results will be discussed. All of these gauges placed in chips and all radial and tangential guages in soil indicated pressures less than about 5 psi. Only the three vertical gauges in soil at the three levels indicated large pressures. The top and middle gauges showed pressures on the order of 35 and 15 psi, respectively, while the bottom gauge indicated a pressure on the order of 50 psi. Ground shock almost certainly produced the higher reading at the lowest level.

b. Scratch Gauges

Gauge scatter appears greater than motions read.

c. Nail Gauges

Horizontal gauges showed little movement. Vertical gauges in chips showed large motions compared with those in soil.

d. Miscellaneous Gauges

These showed that when the earth arches survived, forces in the chips were greatly reduced from those in the soil. Coupled with the vertical nail gauge results above it is concluded that the chips succeeded in providing adequate rattle space without imparting large forces to the items emplaced in chips.

e. All Small Gauges

A number of the small gagues were rotated over 30 degrees and in some cases over 90 degrees. This appears to be the result of rolling or

F' ':RE 17: TUBING FROM 600 PSI LOCATION TOP STATION tumbling the gauge at the interface between two soil masses. This information together with the visible upthrust mounds of dirt at the surface shows there was considerable differential shearing motion or "block motion" of the soil. The upthrust mounds were about 18 inches high at the 600 psi trench and about 8 inches high at the 200 psi trench.

CONCLUSIONS

1. It was demonstrated that a combination of crushable material and soil (deep enough to provide earth arching) protected machines from high overpressure blast and ground shock.

2. It was demonstrated that using the static failure slip angle for average soil (about 30^{0}) to calculate the depth of soil required for arching is approximately correct for dynamic arching. Machines deliberately under-protected were damaged as expected.

3. It was demonstrated that the dirt fill between adjacent machines must be adequate to support the overpressure load. Machines which were placed too closely together resulted essentially in a single wider arch. With insufficient soil depth to "arch" this wider span, the machines were damaged.

4. The passive gauges used gave useful information on gross soil motions, but were not adequate to provide information on the motion at the soil/aluminum chip boundary. Understanding the motions at this boundary will be important for designing better soil/crushable medium combinations.

5. The water filled tanks all received hydraulic shock damage which bulged the walls outward. They would have been repairable in a short time but a method of preventing hydraulic shock would be necessary to prevent any damage.

RECOMMENDATIONS

The subject program was a feasibility demonstration only. Because of its success a scientific/engineering program should be initiated to obtain a more thorough understanding of the basic elements of this hardening technique. Included should be:

1. A range of soil properties (slip planes, strengths, saturations, etc.).
2. A range of crushable material properties (densities, stress-strain relationships, sensitivity to loading rate, etc.).
3. Active instrumentation to give the time variation of soil and crushable material properties and particularly the dynamic motion of the soil/crushable material interface under dynamic loading conditions.
4. Blast tests on machines hardened using the most promising techniques. Either subscale laboratory tests or full scale field tests will provide the desired evaluation. We recommend a combined approach to realize the advantages of both types of testing.*
5. A continuing analytical effort (in parallel with the experimental tasks described above) to formulate and verify a set of practical design guidelines for rapid and inexpensive protection of critical industrial machines.

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*Subscale experiments in facilities such as the U.S. Army Waterways Experiment Station's Large Blast Load Generator or the Air Force Weapons Laboratory's Giant Re-usable Air Blast Simulator (or perhaps a simpler non-explosive loading device) offer rapid turn-around and low cost. Full scale field tests, particularly HEST - type tests (which can simulate nuclear airblast impulse magnitudes) require more flow time and resources but provide greater credibility than subscale tests.

APPENDIX
DETAILED TEST RESULTS

MACHINES

600 PSI

LOWEST LEVEL

1.* MINIBIKE - Surrounded by 1 ft. of chips and covered with 4 ft. of soil. Undamaged except handlebars, fork and front fender misaligned a few degrees.

Vertical nail gauge in soil on top of chips. Corners compressed to 0.60", 0.68", 0.70" and 0.50". Vertical crush guage in soil on top of chips indicates overpressure of order 50 psi.

2. DESK CALCULATOR - Top of chips 6 ft. below post shot grade. Little visible damage, but would only add and subtract. Carriage shift did not work. Repairable.

3. HAND CALCULATOR - Placed in chips. Undamaged.

4. POCKET WATCH - Placed in chips. Was set at 2:14:22 and shock did not cause it to run. Undamaged.

5. "GOT-A-MINUTE" GAME in chips. Not broken. Front tipped down 20^{o} toward GZ. Dice scrambled.

6. 49 MIL 6" PIPE in chips. (Note: all dimensions are outer dimensions.) North end 5 7/16" x 6 11/16" and South end 5 3/8" x 6 5/8".

7. & 9. GAUGES (See below.)

8. 49 MIL 6" PIPE. In soil, tangent to GZ 81" down after shot. Not dimpled. 5.5" x 6 5/8" and 5 3/8" x 6 3/4".

MIDDLE LEVEL

Items in chips with 2 ft. of soil cover:

10. DESK CALCULATOR Carriage bent. Keyboard would not enter. Nothing functioned.

11. HAND CALCULATOR Worked normally.

12. "GOT-A-MINUTE" GAME Plastic cube. Tilted on one edge. Hourglass in bottom, most sand away from GZ but some in side toward GZ. Dice jumbled and two on top of others. (Sand in hourglass was towards GZ initially)

*Item numbers keyed to Figures 2 through 4.

Pipes in loose chips:

13. 49 MIL PIPE tangential to GZ. South end canted up about 20^{0}. Highest point of south end 42 in. below post shot grade. North end flattened 2 7/8" x 8", center dimpled. South end 6 1/8" x 5 7/8" with long axis 30^{0} off vertical.

14. 83 MIL 6 IN. PIPE tangent to GZ. South end tilted up about 30^{0}, vertical 5 15/16" horizontal 6 1/16". North end dented, 2" x 8 1/2".

15. 187 MIL 6 IN. PIPE - South end tilted up about 5^{0} and moved toward GZ about 10^{0}. North end 6 9/16" x 5 7/16" and South end 6 1/16" x 6 1/16".

16. 83 MIL 6 IN. PIPE radial to GZ. End away from GZ tilted up about 20^{0}. East*end vertical 5 5/8", horizontal 6 3/8". West*end vertical 2 3/4", horizontal 8 1/4". Dimple on bottom.

17. GAUGES (See below.)

Pipes in soil: 18, 19 and 20 all level. Topsoil down 41" to post shot grade. None were dimpled.

18. 49 MIL 6 IN. PIPE tangent to GZ. Vertical 5 3/4" x Horizontal 6 3/8" North end; Vertical 5 7/8" x Horizontal 6 1/16", South end.

19. 83 MIL 6 IN. PIPE tangent to GZ. Vertical 5 5/8" x Horizontal 6 3/8" North end; Vertical 5 5/8" x Horizontal 6 3/8" South end.

20. 187 MIL 6 IN. PIPE tangent to GZ. Vertical 6 3/32" x 5 15/16" North end; Vertical 6 1/16" x 6" South end.

21. GAUGES (See below.)

TOP LEVEL

One foot earth above chips.

General comments on top level chip station: There was one large flat chip area with bags of chips below and above the test items. On recovery soil had been injected between all the bags of both layers. About as much soil by volume as the chip bag volume was injected.

22. DESK CALCULATOR - Top and back smashed, carriage bent, keyboard essentially undamaged. Calculator damaged beyond repair.

* West is towards GZ. East is away from GZ

23. HAND CALCULATOR - Case undamaged. Display lit-up initially, but then calculator failed.

24. "GOT-A-MINUTE" GAME smashed to small pieces which were not all recovered.

The next four items were 6 inch aluminum pipes in chips. The first three were tangent to GZ and the fourth radial. The smaller dimensions recorded were the vertical end dimensions, but a record was unfortunately not made of the direction corresponding with each set of measurments.

25. 49 MIL wall thickness. Dimpled on bottom. End dimensions were 2 7/8" x 8 3/8" and 2" x 8 5/8".

26. 83 MIL wall thickness. Tilted up 10^{0} on south end. Top and bottom split. End dimensions were 2 7/8" x 8 1/2" and 1" x 9 1/4".

27. 187 MIL wall thickness. Dimpled top and bottom. End dimensions were 3 5/8" x 7 3/4" and 5 1/2" x 6 5/8".

28. 83 MIL wall thickness. End toward GZ sloped down 10^{0}. End dimensions were 1 3/8" x 9 1/8" and 4 3/4" x 7". Latter end dimpled on bottom.

29. GAUGES (See below.)

Items 30. through 32. were 6 inch aluminum pipes placed in soil tangent to GZ.

30. 49 MIL wall thickness 34" to post shot grade. Dimpled on bottom. End dimensions 5 1/4" x 6 5/8" and 5 1/4" x 6 11/16".

31. 83 MIL wall thickness 34" to post shot grade. End dimensions 4 3/4" x 6 5/8" and 4 3/4" x 6 3/4", bottom dimpled.

32. 187 MIL wall thickness, 35" below post shot grade. <u>No damage</u>.

33. GAUGES (See below.)

<u>200 PSI</u>

1. VARIDRIVE - No damage. Top of large scratch gauge on top 18" below post shot grade. Perm. movement 0.33", scratch length 2.48". Top of plastic 41" below post shot grade.

2. VARIDRIVE - Top of large scratch gauge 29" below post shot grade. Perm. movement 1 7/8". No scratch. Only visible damage to varidrive was 1 in. slide of V drive pulley on electric motor shaft, so belt was out of line.

3. ELECTROLYTIC GRINDER (Large machine) Top of large scratch gauge 31" below post shot grade. Perm. movement 2". No scratch. Only visible damage to grinder was bent lamp support and loosened motor mount.

4. CALCULATOR (All calculators from this point on are desk calculators.) - In aluminum chips in garbage can tangent to GZ. Top of can 4' 7" below post shot grade. About 2" gap between top of chips and top of can post shot. Right end of calculator carriage bent down about 1/4". No other visible damage. Would only add and subtract. Carriage would not shift.

5. DOUBLE WALLED TANK - Top of large scratch gauge 25" below post shot grade. Perm. movement 2.55", scratch length 4.15". Top of plywood 54" below post shot grade. Outer tank was empty. Water was down 4" below plywood in inner tank. Inner tank sides bulged out about 2". Damage repairable.

6. SINGLE WALLED STEEL TANK - Large scratch gauge on top, perm. movement 1 9/16", no scratch. Preshot setting 26" from top of top plate to bottom of bottom plate. Plywood 4' 4" below post shot grade. Plywood edge away from GZ 2" higher than front edge. Plywood appears level in north-south direction. No water in tank when plywood cover removed. Tension tears in plastic lining in all four bottom corners in both layers of plastic. This indicates water was present until shock wave arrived. South end (base of electronic cabinet) dished in on all four sides. Lips on sides of top bent down (45^0 on GZ side and 30^0 on opposite side). Long sides dished in about 1/2".

7. GAUGES (See below.)

8. CHAIN HOIST - No visible damage. Styrene base cracked in 3 places. Depth of base from post shot grade was 6' 4".

9. GAUGES (See below.)

10. CHAIN HOIST - Top of large scratch gauge 20" below post shot grade. Perm. movement 1 1/16". Scratch indicated upward movement of top plate of 2 1/16" followed by downward movement of 3 1/4". No visible damage to hoist.

11. CALCULATOR - Top of garbage can 3' 5" below post shot grade. Calculator badly damaged -- carriage crushed, left side of case cracked, keyboard dented in. Irreparable damage.

12. CALCULATOR - Top of garbage can 2' 8" below post shot grade. Gap (3 1/2") between can and chips in top North region of can. Both ends of carriage crumpled about 1/2". Bottom dished up 1/2". Motor ground. Nothing worked.

13. CALCULATOR - Top of garbage can 2' 2" below post shot grade. Both ends of carriage crumpled and bent. Right end bent down about 20^{o}. Keyboard dished in about 3/4". Irreparable damage.

14. CALCULATOR - Top of garbage can 1' 4" below post shot grade. Gaps (2" and 3", respectively) in south and north regions of can. Minimal visual damage. Motor ran. Carriage jammed. Nothing worked. All but carriage repairable.

15. CALCULATOR - Motor ran, carriage did not work, keyboard did not enter, case back spring. Irreparable.

16. UNPROTECTED CALCULATOR - Top of calculator 16" below post shot grade. Case dished in all around and loose from works which were also bent. Irreparable damage.

<u>80 PSI</u>

1. GAUGES IN SOIL (See below.)

2. CALCULATOR - Top of small scratch gauge 13" below post shot grade. Perm. movement 0.62", scratches 0.95" in compression and 0.10" in expansion. Top f chips 24" below post shot grade. No visible damage to calculator. Carriage shift worked, added, subtracted and divided at first, but then jammed.

3. VARIDRIVE - Top of small scratch guage 18" below post shot grade.

Perm. compression 0.62" scratch 1.18" in compression. No visible damage to varidrive.

4. CHAIN HOIST - No visible damage.

5. CALCULATOR - Top of small scratch gauge 17" below post shot grade. Perm. compression 0.85", scratch 1.18" in compression. No visible damage to calculator.

6. CALCULATOR - Top of small scratch gauge 12" below post shot grade. Top of gauge tilted 10^{o} toward south. Permanent compression 0.58", scratch 0.82" in compression. Top of chips 23" below post shot grade. Carriage and bottom dented about 1/4". Carriage shifted reluctantly. Added, subtracted and divided but carriage jammed. Repairable.

7. CALCULATOR - Top of small scratch gauge 15" below post shot grade. Permanent compression 0.82", scratch 1.18" in compression. Little visible damage to calculator. Added, subtracted and divided. Needs minor repair.

8. CHAIN HOIST - Top of small scratch gauge 12" below post shot grade. Permanent compression 7/16", scratch 5/8" in compression. Top of hoist (not chips) 34" below post shot grade. No visible damage to hoist.

9. VARIDRIVE - Top of small scratch gauge 17" below post shot grade. Permanent compression 0.50", scratch 0.75" in compression. No visible damage to varidrive.

10. UNPROTECTED CALCULATOR (Printing adding machine) - Top of small scratch gauge 27" below post shot grade. Plates of gauge separated 12 1/8" end-to-end. Permanent compression 0.95", scratch 0.95" in compression and 0.22" in expansion. Top of calculator (not chips) 39" below post shot grade. Thumb wheel on machine broken. Motor didn't run. Keyboard didn't work. Machine completely "inert".

11. UNPROTECTED CALCULATOR - Top of small scratch gauge 16" below post shot grade. Permanent compression 0.87", scratch length 1.10". Carriage jammed. Small dents. Motor grinds. Nothing works. Irreparable damage.

12. CHIP BREAKER GRINDER (Large machine) (No gauge information recorded) Some bending of sheet metal parts on top and bottom. Flanges bent inward 1" on top and 2" on bottom. Damage easily repairable.

13. GAUGES IN SOIL (See below.)

14. GAUGES IN ALUMINUM CHIPS IN GARBAGE CAN (See below.)

15. DOUBLE WALLED TANK - Top of large scratch gauge 9" below post shot grade. Permanent compression 1 9/16", scratch length 2 1/4". Plywood cover bowed up on all edges. Center about 1" lower than edges No apparent tilting. About 1/2" of water in bottom of tank. No obvious tears in plastic liner. Some evidence that water leaked out before shot day. The outer tank walls were pushed in almost to the inner wall.. (This could have happened during emplacement.) The inner tank walls were bulged outward and the lips bent downward and crinkled. There were no tension tears in the plastic corners, but there was a puncture tear in one corner. The styrofoam base punched through to a depth of 1".

16. SINGLE WALLED TANK - Top of large scratch gauge 10" below post shot grade. Permanent compression 1.62", scratch 2.62" in compression. Plywood 38" below post shot grade. Plywood corner of tank tilted downward -- South end 2" lower than north end. Southwest corner of tank punched through plywood. About 1" of mud in tank bottom. Tension tears in both south corners of plastic liner. Water erosion marks in mud at both corners. All four walls of tank bulged outward.

    West wall (toward GZ) bulged 1" toward GZ.

    East wall bulged 2" away from GZ.

    North wall bulged out 2".

    South wall bulged out 1". Rims bent down about 45^{0} (except south rim undamaged).

<u>40 PSI</u>

1. CALCULATOR - Gauge damaged on recovery. Top of chips 30" below post shot grade. Little visible damage. Added and subtracted. Repairable.

2. CALCULATOR - Top of small scratch gauge 15" below post shot grade. Perm. compression 0.53", scratch length 0.65". No visible damage to calculator. Would not multiply but damage easily repairable.

3. CHAIN HOIST - Top of small scratch gauge 15" below post shot grade. Perm. compression 0.5", scratch length 0.6". Top of chips 28" below post shot grade. No visible damage to hoist.

4. VACUUM PUMP - Top of small scratch gauge 17" below post shot grade. Gauge 14" end-to-end. Perm. compression 0.43", scratch 0.74" in compression. No visible damage to pump.

5. TWO COMPARTMENT STEEL TANK _ Two small scratch gauges set on plywood cover. Top of south gauge 20" below post shot grade. Perm. compression 0.83", scratch length 1.25". Top of north gauge 20" below grade. Gauge base tilted - higher on north end. Perm. compression 1.10", scratch length 1.40". Plywood (slightly warped) 30" below post shot grade. Only 1/2" water in tank. Rips 3" long in 3 bottom corners of plastic liner. Outer tank end walls bulged out about 1/2". Inner wall bulged away from GZ about 2". One bottom door bent up about 1 1/2".

6. POWER SUPPLY FOR ITEM 12 AT 80 PSI - Top of small scratch gauge 14" below post shot grade. Gauge length end-to-end was 13". Permanent compression 0.30", scratch 0.70" in compression. Top of chips 27" below post shot grade. Bottom of power supply (would be back side in factory use) was bent upward about 1" in two areas separated by a center brace. Also, an airvent on one side was broken loose from a spot weld at one end and pushed inward about 2". By visual inspection the operation of the power supply would not be impaired by this easily repairable damage.

7. GAUGES IN SOIL (See below.)

8. GAUGES IN ALUMINUM CHIPS IN GARBAGE CANS (See below.)

9. CHAIN HOIST - Top of small scratch gauge 24 1/2" below post shot grade. Permanent displacement 0.90", 1.55" scratch length. Top of chips 46" below post shot grade. No visible damage to chain hoist. (Accidentally covered with dirt in wall cave-in after uncovering.)

10. CALCULATOR - Large scratch gauge on top had permanent 1.67" compression and a 1.90" compression scratch. Little visible damage to calculator. Added and subtracted. Repairable.

11. VARIDRIVE - Top of small scratch gauge 22" below post shot grade. Perm. motion 0.23", scratch length 0.55". No visible damage.

12. CALCULATOR - Top of small scratch gauge 25" below post shot grade. Perm. compression 0.55", scratch compression 0.75". Little visible damage. Did not multiply. Easily repairable.

13. ADDING MACHINE - Top of small scratch gauge 19.5" below post shot grade. Perm. displacement 0.90", scratch length 1.56". Vertical nail gauge at 12" depth initially set to 1" compressed to 0.70", 0.53", 0.52", and 0.69" at the four corners. Horizontal nail gauge corners: 1.0", 1.05", 1.08" and 0.95". No visible damage to calculator. Undamaged except for one sticking number key.

14. CALCULATOR - Confusion in field notes concerning small scratch gauge details. NOTE SET 1: Top of gauge 18" below post shot grade. Perm. compression 0.55", scratch compression 0.60". Top of chips 30" below post shot grade. NOTE SET 2: Top of guage 14" below post shot grade. Perm. compression 0.67", scratch compression 0.90". Top of calculator 36" below post shot grade. The calculator keyboard would not enter and the carriage was slightly bent. Motor and dials ran continuously. Nothing worked.

GAUGES

<u>600 PSI</u>

LOWEST LEVEL

7. GAUGES IN LOOSE CHIPS UNDER MINIBIKE

All 7' 4" below post shot grade.

a. Radial crush gauge. No measurable indentation.

b. Radial nail gauge. 1.0" x 0.93" x 0.95" x 1.0" (Shorthand notation for corner gap readings.)

c. Tangential crush gauge. No measurable indentation.

d. Vertical beer can. Crushed (column failure). Shortened 3/8".

e. Tangential nail gauge. Rotated about 35°. 1.0" x 1.0" x 1.05" x 1.1".

f. Vertical water glass survived.

g. Vertical light bulb survived.

h. Vertical crush gauge (stayed vertical). No measurable indentation.

i. Vertical nail gauge. 0" x 0.15" x 0.42" x 0.30".

j. Radial beer can. Minor crushing (1/2" indentations).

k. Radial water glass survived.

l. Tangential beer can. Minor crushing (1/4" indentations).

m. Tangential drinking glass survived.

n. Tangential light bulb smashed.

o. Radial light bulb smashed.

9. GAUGES IN SOIL 7' 6" below post shot grade. The stratum containing these gauges was tilted up about 5^{0} on the GZ end and arched up about 1" in two horizontal feet in the north-south direction.

   a. Vertical, radial and tangential light bulbs all crushed.
   b. Vertical ale can. Top tilted about 10^{0} towards south. Crinkles about 1/2" deep all around can.
   c. Radial and tangential ale cans. Longitudinal crinkles about 3/4" deep.
   d. Vertical nail gauges. Top tilted about 10^{0} to south. 0.38" x 0.38" x 0.43" x 0.33".
   e. Radial nail gauge. 1.0" x 0.98" x 0.93" x 0.95".
   f. Tangential nail gauge. 1.0" x 1.0" x 1.05" x 1 05".
   g. Vertical crush gauge. Front tilted about 10^{0} away from GZ and top tilted toward south about 10^{0}. Gauge indicated a pressure of order 50 psi.
   h. Radial and tangential crush gauges. Top tilted about 10^{0} away from GZ. No measurable indentations.
   i. Vertical drinking glass. No damage.
   j. Radial and tangential drinking glasses crushed.

MIDDLE LEVEL

17. GAUGES IN CHIPS

a. Vertical and radial light bulbs smashed. Tangential light bulb undamaged.

b. Vertical drinking glass undamaged, but tilted about 45^{o} to south.

c. Radial drinking glass undamaged, but rotated 90^{o} to tangent position.

d. Tangential drinking glass not damaged, but (open) south end tilted up about 10^{o}.

e. Vertical soft drink can tilted 90^{o} away from GZ to radial position. Column crushing and end bent. Dents about 1" deep.

f. Radial soft drink can rotated almost to tangent position with top 10^{o} above horizontal and 15^{o} toward GZ. Can crinkled all around with dents 1/2" deep.

g. Tangential soft drink can rotated to 30^{o} from horizontal and 30^{o} from radial. Bottom was up and towards GZ. Longitudinal 1/2" crinkling.

h. Vertical crush gauge. Top tilted almost horizontal to north. Indentations not measurable.

i. Radial crush gauge rotated to tangent position and tilted 45^{o}. Side toward GZ up 45^{o}. Indentations not measurable.

j. Tangential crush gauge rotated to almost radial. Bottom towards GZ and about 15^{o} above horizontal. Indentations not measurable.

k. Vertical nail gauge. Top tilted to north to a horizontal position. Nails driven all the way into balsa block.

l. Radial nail gauge. Top down 10^{o} towards south and front up 15^{o} toward GZ. 1.1" x 0.98" x 1.03" x 1.10".

m. Tangential nail gauge rotated to radial position. 0.85" x 0.80" x 0.95" x 1.0".

21. GAUGES IN SOIL

a. Vertical, radial and tangential light bulbs all smashed. All shortened to about half their original length and flattened.

b. Vertical soft drink can -- 1/2" compression crinkles.

c. Radial and tangential soft drink cans -- 3/8" longitudinal crinkles. Also flattened on top.

d. Drinking glasses -- Vertical glass intact and uncracked. Tangential and radial glasses smashed. No apparent displacement of any of the glasses.

e. Vertical crush gauge. Indicates pressure of order 15 psi.

f. Vertical nail gauge 0.60" x 0.68" x 0.70" x 0.50".

g. Vertical nail gauge top tilted towards north 0.31" x 0.25" x 0.30" x 0.36".

h. Tangential nail gauge - 1" x 1" x 1" x 1".

i. Radial nail gauge 1.1" x 1" x 1.05" x 1.03".

TOP LEVEL

29. GAUGES IN CHIPS BETWEEN PIPES 25 THROUGH 28

    a. Water glass smashed.
    b. Vertical nail gauge. Nails driven all the way into balsa block.
    c. Vertical soft drink can smashed flat. (Column failure offset to one side.)
    d. Radial soft drink can. Crushed (to half its original volume) on all sides and on end facing GZ.
    e. Tangential soft drink can smashed flat.
    f. Vertical crush gauge. Indentations not measurable.

33. GAUGES IN SOIL BETWEEN PIPES 30 THROUGH 32

    a. Vertical nail gauge. Top tilted 45^0 toward GZ 0.78" x 0.38" x 0.38" x 0.76".
    b. Vertical crush gauge. Indicates pressure of order 35 psi.
    c. Vertical soft drink can. Classic column failure.
    d. Radial soft drink can. Crushed.
    e. Tangential soft drink can crushed.
    f. Drinking glass smashed.

200 PSI

7. GAUGES IN SOIL

DEPTH OF GAUGE TOP BELOW POST SHOT GRADE	DESCRIPTION
6 in.	Small vertical scratch gauge. Perm. compression 1.37", scratch length 1.86".
7 in.	Large horizontal scratch gauge. Perm. compression 0.1", scratch length 0.45".
11 in.	Horizontal nail gauge. 1.0" x 1.0" x 1.0" x 0.95".
11 in.	Vertical nail gauge. 0.60" x 0.60" x 0.58" x 0.58".
13 in.	One gallon can. 0.3" dents.
18 in.	Small vertical scratch gauge. Perm. compression 1.10", scratch length 1.70".
22 in.	Large horizontal scratch gauge. Perm. compression 0.15", scratch length 0.27".
25 in.	One gallon can. 0.32" dents (less damage than can at 13 in.)
26 in.	Vertical nail gauge. 0.50" x 0.40" x 0.42" x 0.56".
28 in.	Horizontal nail gauge. 0.95" x 0.95" x 1.0" x 1.0".
28 in.	Small vertical scratch gauge. Perm. compression 1.20", scratch length 2.05".
35 in.	Large horizontal scratch gauge. Perm. compression 0.03", scratch length 0.42".
36 in.	One gallon can. 0.3" dents.
37 in.	Vertical nail gauge 0.42" x 0.42" x 0.48" x 0.46".
40 in.	Small vertical scratch gauge. Perm. compression 1.36", scratch length 2.4".
41 in.	Horizontal nail gauge. 0.95" x 1.0" x 1.0" x 0.98".

44 in.	Large horizontal scratch gauge. Perm. compression 0.42", scratch length 0.80".
50 in.	Horizontal nail gauge. 1.05" x 1.05" x 1.05" x 0.95".
50 in.	One gallon can. 0.50" dents.
51 in.	Small vertical scratch gauges. Perm. compression 1.22", scratch length 1.92".
53 in.	Large horizontal scratch gauge. No perm. motion, scratch length 0.1".
59 in.	One gallon can. 0.43" dents.
61 in.	Vertical nail gauge. 0.47" x 0.30" x 0.32" x 0.38".
61 in.	Horizontal nail gauge. 1.0" x 0.95" x 0.95" x 1.0".

9. GAUGES IN ALUMINUM CHIPS IN GARBAGE CAN COLUMN

DEPTH OF GAUGE TOP BELOW POST SHOT GRADE	DESCRIPTION
19 in.	Small vertical scratch gauge. Perm. compression, 2.7[illegible]", scratch length 2.98" Completely collapsed (probably stepped on in recovery).
26 in.	Vertical nail gauge. 0.82" x 0.90" x 0.88" x 0.80".
26 in.	Horizontal nail gauge. 1.0" x 0.95" x 0.94" x 0.98".
26 in.	Soft drink can. Minor crushing (0.3") of bottom.
29 in.	Small vertical scratch gauge. Perm. compression 1.35", scratch length 2.30 in.
46 in.	Vertical nail gauge. 0.75" x 0.78" x 0.85" x 0.83".
48 in.	Horizontal nail gauge. 0.92" x 0.94" x 0.98" x 0.96".

45 in.	Small vertical scratch gauge. Perm. compression 0.93", scratch length 2.30".
53 in.	Vertical nail gauge. 0.82" x 0.80" x 0.75" x 0.73".
53 in.	Horizontal nail gauge. 1.02" x 0.95" x 0.88" x 0.92".
53 in.	Ale can. Top and bottom each crushed in about 0.4".
56 in.	Small vertical scratch gauge. Perm. compression 0.95", scratch length 2.02".
65 in.	Vertical nail gauge. 0.45" x 0.52" x 0.85" x 0.82".
65 in.	Horizontal nail gauge. 0.90" x 0.88" x 1.0" x 1.0".

80 PSI

1. GAUGES IN COMPACTED SOIL

DEPTH OF GAUGE TOP BELOW POST SHOT GRADE	DESCRIPTION
7 in.	One gallon can, GZ end tilted down about 10^o. Top dented in 0.50", bottom bulged down about 0.25", sides dented in 0.60" and 0.50".
7 in.	Vertical nail gauge. GZ end tilted up about 10^o. 0.33" x 0.30" x 0.28" x 0.33".
8 in.	Tangential nail gauge. 1.0" x 0.90" x 0.80" x 0.90".
20 in.	Small radial scratch gauge. Perm. compression 0.87", scratch length 0.90".
22 in.	Small vertical scratch gauge. Perm. compression 1.56", no scratch.
23 in.	One gallon can. Side toward GZ tilted up about 5^o. Top bottom and sides dented in 0.60", 0.36", 0.60" and 0.40", respectively.
23 in.	Vertical nail gauge. 0.53" x 0.55" x 0.55" x 0.52".
24 in.	Radial nail gauge. North side tilted downward about 10^o. 0.90" x 0.93" x 1.05" x 1.0".
32 in.	Vertical nail gauge. 0.48" x 0.60" x 0.65" x 0.50".
32 in.	Radial nail gauge. 1.05" x 0.98" x 0.94" x 1.06".
32 in.	One gallon can, GZ end tilted up about 10^o. Top, bottom and sides dented in 0.55", 0.35", 0.60" and 0.45", respectively.

13. GAUGES IN LOOSE SOIL

DEPTH OF GAUGE TOP BELOW POST SHOT GRADE	DESCRIPTION
20 in.	Large vertical scratch gauge. Perm. compression 1.57", scratch 2.56" in compression.
32 in.	Large radial scratch gauge. Perm. compression 0.07", scratch length 0.40".
36 in.	Radial nail gauge. 1.0" x 1.0" x 1.0" x 1.0".
36 in.	Vertical nail gauge 0.55" x 0.55" x 0.72" x 0.72".
36 in.	One gallon can. Top dented in 0.3". Two 0.6" dents in bottom. Sides crinkled in 0.40" and 0.38".
37 in.	Large radial scratch gauge. No permanent motion. Scratch length 0.25" in compression.
41 in.	Vertical nail gauge. Tilted 20^{0} towards north. 0.78" x 0.67" x 0.83" x 1.0".
41 in.	Radial nail gauge. 1.0" x 1.0" x 0.92" x 0.92".
41 in.	One gallon can. Top, bottom and sides dented 0.48", 0.43", 0.55" and 0.30" respectively.
43 in.	Large vertical scratch gauge. Perm. compression 2.0", scratch lengths 2.70" in compression and 0.08" in expansion.
52 in.	Large radial scratch gauge. Perm. compression 0.15", scratch lengths 0.20" in expansion and 0.32" in compression.
52 in.	One gallon can. Top, bottom and side dents 0.38", 0.58", 0.50" and 0.50", respectively.
54 in.	Vertical nail gauge. Top tilted about 10^{0} to north. 0.55" x 0.58" x 0.58" x 0.62".
54 in.	Radial nail gauge. 0.91" x 0.93" x 1.0" x 0.98".

66 in.	Vertical nail gauge. 0.60" x 0.38" x 0.45" x 0.70".
66 in.	Tangential nail gauge. 1.02" x 1.0" x 1.0" x 1.02".
68 in.	One gallon can. Top, bottom and sides dented in 0.68", 0.22", 0.60" and 0.50", respectively.

14. GAUGES IN ALUMINUM CHIPS IN GARBAGE CAN COLUMN

DEPTH OF GAUGE TOP BELOW POST SHOT GRADE	DESCRIPTION
16 in.	Small vertical scratch gauge. Perm. compression 1.24", scratch length 2.18".
25 in.	Vertical nail gauge. 0.96" x 0.95" x 0.92" x 0.88".
25 in.	Horizontal nail gauge. 1.04" x 1.0" x 1.0" x 0.98".
25 in.	Ale can. No damage.
28 in.	Small vertical scratch gauge. Perm. compression 1.03", scratch length 1.64".
37 in.	Vertical nail gauge. 0.72" x 0.68" x 0.86" x 0.88".
37 in.	Horizontal nail gauge. No movement.
44 in.	Small vertical scratch gauge. Top tilted a bit toward GZ. Perm. compression 0.82", scratch length 1.80".
52 in.	Vertical nail gauge. 1.0" x 0.98" x 0.92" x 0.90".
52 in.	Horizontal nail gauge. 1.0" x 1.0" x 1.0" x 0.98".
52 in.	Ale can. No damage.
56 in.	Small vertical scratch gauge. Perm. compression 1.13", scratch length 2.15".
64 in.	Vertical nail gauge. 0.73" x 0.76" x 0.94" x 0.88" (small dimensions away from GZ).
64 in.	Horizontal nail gauge. 1.0" x 0.98" x 1.03" x 1.05".

40 PSI

7. GAUGES IN SOIL

DEPTH OF GAUGE TOP BELOW POST SHOT GRADE	DESCRIPTION
4 in.	Large vertical scratch gauge. Perm. compression 2.42", no scratch.
18 in.	Vertical nail gauge. 0.48" x 0.53" x 0.56" x 0.46".
13 in.	Horizontal nail gauge. 0.9" x 0.95" x 1.0" x 0.95".
18 in. (?)	One gallon can smashed by front loader.
19 in.	Large vertical scratch gauge. Perm. compression 3.0", scratch length 1.2".
24 in.	One gallon can. Top, bottom and sides dented in 1", 1", 0.5" and 0.5", respectively.
40 in.	One gallon can. Top, bottom and sides dented in 0.6", 0.5", 0.5" and 0.5", respectively.

8. GAUGES IN ALUMINUM CHIPS IN GARBAGE CAN COLUMN

DEPTH OF GAUGE TOP BELOW POST SHOT GRADE	DESCRIPTION
17 in.	Small vertical scratch gauge. Perm. compression 1.15", scratch length 1.73".
25 in.	Vertical nail gauge. 0.96" x 1.0" x 1.0" x 0.96".
25 in.	Horizontal nail gauge 1.0" x 0.98" x 0.96" x 0.96".
25 in.	Ale can undamaged.
29 in.	Small vertical scratch gauge. Perm. compression 1.08", scratch length 1.58".
36 in.	Vertical nail gauge. No movement.
36 in.	Horizontal nail gauge. 1.0" x 1.05" x 1.05" x 1.0".
43 in.	Small vertical scratch gauge. Perm. compression 0.65", scratch length 1.12".

51 in.	Vertical nail gauge. 0.98" x 1.0" x 1.0" x 0.95".
51 in.	Horizontal nail gauge. No movement.
51 in.	Ale can undamaged.
54 in.	Small vertical scratch gauge. Perm. compression 1.0", scratch length 1.48".
64 in.	Vertical nail gauge. No movement. Gauge tilted away from GZ 45^0 (installation problem?).
64 in.	Horizontal nail gauge. No movement.

MISCELLANEOUS OBSERVATIONS

1. Heavy studded "T" fence post at NW corner of 600 psi trench sheared off 14" below post shot grade.

2. There are light and dark strata in the vicinity of the power supply and tank at 40 psi. These strata allowed some arching details to be seen. The north edge of the tank plywood cover was 3.5 ft. south of the chips surrounding the power supply. The soil compressed to the north of the power supply so an arch was formed over and to the north of this machine. The tank appeared to take the load and kept the soil from compressing over the tank. An arch formed to the north and south of the tank. The arch to the north of the tank sheared the arch to the south of the power supply. The shear was 11" in a horizontal span of 36".

DEFINITIONS OF TERMS AND ACRONYMS

AFB	Air Force Base
ANFO	Ammonium nitrate fuel oil explosive
Chimneying	Falling of material from the roof of a cavity or opening. Falling of one layer permits the next layer to fall. The falling or collapse may progress upwards until the surface is reached.
DNA	Defense Nuclear Agency
Earth Arching	Ability of earth to support loads above an opening by providing a load path around the opening.
ft	Foot
ft^3	cubic foot
GZ	Ground zero
in	inch
Kt	Kiloton
lb	pound
mil	one thousandth of an inch
psi	pounds per square inch
TNT	Trinitrotoluene
o	degree
"	inch
'	foot

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